

Semi-Annual Progress Report
Determination of the Emissivity of Materials

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FOREWORD

This report describes the research activity carried out in fulfillment of Contract NAS3-4174 during the period from November 15, 1964, through May 14, 1965. The work was conducted under the direction of the Space Power Systems Division, Lewis Research Center, National Aeronautics & Space Administration, with Robert L. Davies as Project Manager.

ABSTRACT

The testing of coatings for use on space radiators was continued during the report period. A total of seven materials were tested on either AISI-310 stainless steel or columbium-1 percent zirconium tubes.

To date, best results have been obtained with iron titanate and calcium titanate coatings. An iron titanate coating on AISI-310 stainless steel has been tested at 1350°F in a vacuum of about 2×10^{-8} mm Hg for 5300 hours. An emittance of 0.88 or better was obtained throughout the period. A second iron titanate coating on columbium-1 percent zirconium has been tested at 1700°F for 6250 hours with an emittance of 0.85 or better throughout the test. A coating of calcium titanate on AISI-310 stainless steel has been tested for 6300 hours at 1350°F with an emittance of about 0.90 throughout the tests. Adherence tests have been conducted for both of the coatings and the bond strengths were found to be excellent.

A fourth long-term endurance test is being conducted on an aluminum oxide-aluminum titanate coating on columbium-1 percent zirconium. A total of 1000 hours have been accumulated to date with an emittance which has slowly decreased from 0.85 to 0.83.

Short-term endurance total hemispherical emittance tests were conducted at 1700°F on coatings of a stabilized titanium oxide composition, zirconium titanate, and barium titanate applied to columbium-1 percent zirconium tubes. The stabilized titanium oxide composition displayed an emittance of about 0.87 during 294 hours of testing. An additional test was initiated in a long-term endurance total hemispherical emittance rig. However, after an additional 100 hours, the coating separated from the substrate in localized areas and the emittance dropped to an unacceptable level. The test was repeated with another specimen, but the results were similar. Both zirconium titanate and barium titanate were rejected for long-term endurance testing because both had emittance levels below 0.85 before the completion of short-term testing.

An analysis was conducted to determine the temperature drop across the walls of the tubes used for substrates since temperature measurements are made with thermocouples on the outer surface and with an optical pyrometer on the inner surface. The analysis indicated that, with the most adverse conditions experienced during the current test program, the temperature drop would not exceed 0.5°F and therefore could be neglected.

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I. INTRODUCTION

A program is being conducted to determine the suitability of selected high-emittance materials for use as coatings on nuclear space power-plant radiators. The coating materials are being evaluated at elevated temperatures and high vacuum for their emittance stability, adherence, and compatibility when applied to AISI-310 stainless steel or columbium-10 percent zirconium. This report describes the work conducted during the second six months of the program. The work conducted during the first six months was reported in detail in the first semi-annual report (CR-54268).

II. BACKGROUND

During the first six months of the program, the four total hemispherical emittance rigs used in a previous program were modified to permit specimens to be tested at temperatures up to 1800°F at pressures lower than 10^{-7} mm Hg for periods in excess of 5000 hours.

Several coating materials were subjected to short-term emittance testing to determine their suitability for long-term testing. Calcium titanate and iron titanate were found to be suitable. Consequently, three long-term total hemispherical emittance tests were begun with specimens of AISI-310 stainless steel coated with calcium titanate, AISI-310 stainless steel coated with iron titanate, and columbium-1 percent zirconium coated with iron titanate.

In support of the emittance program, coating adherence tests were conducted by vibrating AISI-310 stainless steel specimens coated with 4-mil thick layers of calcium titanate. No coating separation or spalling occurred during these tests, and the tests were terminated by failure of the substrate.

III. TEST PROCEDURES AND APPARATUS

A. Short-Term Testing

Short-term total hemispherical emittance testing is conducted in the rig shown in Figure 1. This rig permits emittance tests to be conducted at temperatures up to 2000°F at pressures in the 10^{-8} mm Hg range.

The specimens used for emittance testing are coated AISI-310 stainless steel or columbium-1 percent zirconium tubes 9 inches long and 0.250 inch in diameter with a 0.010-inch wall thickness. The coatings are applied by plasma-arc spraying to a thickness of about 4 mils.

Short-term emittance testing is conducted to determine the emittance stability of coating-substrate combinations. Specimens with AISI-310 stainless steel substrates are tested at 1350°F, whereas those with columbium-1 percent zirconium substrates are tested at 1700°F. The tests normally are conducted for 250 to 300 hours, provided an emittance of 0.85 or better is achieved. During this period, the specimens are thermally cycled by shutting off the heating power and permitting the specimen to cool to ambient temperature, and then slowly returning it to operating temperature.

After emittance testing, the coating is thoroughly examined for cracking, spalling, or change in texture, and the test chamber is examined for evidence of coating volatilization.

B. Long-Term Testing

Those coatings which display adequate emittance and adherence properties may be selected for extended testing in one of the long-term total hemispherical emittance rigs shown in Figure 2. These rigs permit emittance tests to be conducted at temperatures up to 1700°F at pressures in the 10^{-8} mm Hg range for periods in excess of 10,000 hours.

The specimens used are identical to those used for short-term total hemispherical emittance testing. The long-term test program includes thermal cycling to ambient temperatures after initial heating and after 100, 200, 300, 400, and 500 hours. During the present report period, each specimen was subjected to thermal cycling once each week.

C. Adherence Testing

Coating bond strength is evaluated by vibration testing conducted in the Westinghouse vibration fatigue apparatus shown in Figure 3. With this equipment, fatigue specimens are vibrated at 120 cps at various stress levels. Both coated and uncoated specimens are tested and the number of cycles to failure is plotted as a function of stress. Failure for uncoated specimens is fracture, whereas coated specimens are considered to have failed as soon as cracking, spalling, or separation of the coating occurs if any of these occur before the substrate fractures.

Spalling and cracking can be detected visually, but coating separation can be difficult to discern. Consequently, fatigue specimens are tested in the fatigue specimen inspection rig to determine if separation has occurred (see Figure 4). The specimens are mounted between two tubular end clamps which are supported by copper tubes which serve both as current leads and coolant tubes. The coolant bypasses the specimen through a plastic tube. The specimens are instrumented with three 0.003-inch diameter chromel-alumel thermocouples located at the specimen midpoint and at each end. The specimen is then heated to red heat and examined for color uniformity. A lack of color uniformity qualitatively indicates that separation has occurred since any separation of the coating locally lowers the heat transfer rate between the substrate and the coating, resulting in a lower surface temperature and a dark spot in the area of separation. The specimens were photographed using infrared film to detect the nonuniformities not detectable visually and to provide a record of the test.

IV. TEST RESULTS

The three long-term total hemispherical emittance endurance tests which were started during the previous report period were continued throughout this report period. The three specimens being tested are calcium titanate on AISI-310 stainless steel, iron titanate on AISI-310 stainless steel, and iron titanate on columbium-1 percent zirconium.

The success experienced with titanate coatings in the long-term tests warranted investigation of other titanate materials. Consequently, a total of five short-term tests of four different materials which were wholly or in part of titanate composition were conducted. The materials tested were selected on the basis of previous test results and a survey of the industry and included columbium titanate, zirconium titanate, an aluminum titanate-aluminum oxide composition, and a barium titanate composition. Of these, two coating-substrate combinations (the aluminum titanate-aluminum oxide composition on columbium-1 percent zirconium and columbium titanate on columbium-1 percent zirconium) demonstrated adequate adherence and emittance during short-term testing to qualify for long-term testing.

The adherence of iron titanate on AISI-310 stainless steel and on columbium-1 percent zirconium was evaluated through fatigue testing.

A. Calcium Titanate on AISI-310 Stainless Steel

1. Long-Term Testing

Testing of the AISI-310 stainless steel tube coated with a 4-mil thick calcium titanate coating which had accumulated 2000 hours of endurance testing during the previous report period was continued. An additional 4300 hours were accrued during the current report period for a total test time of 6300 hours at 1350°F.

As shown in Figure 5, the total hemispherical emittance of this specimen was 0.91 for the first 2500 hours and dropped to 0.90 during the next 500 hours. The emittance has remained constant at about 0.90 for the last 3400 hours. Throughout the test, a vacuum of at least 10^{-7} mm Hg has been maintained as shown in Figure 6.

During the report period, the specimen was subjected to 18 additional thermal cycles. The thermal shock tests for this coated tube now total 24. No adverse effects on the emittance or adherence of the calcium titanate coating has resulted.

2. Adherence Testing

The bond strength testing of calcium titanate coatings on AISI-310 stainless steel was completed during the report period. Fatigue tests were conducted during the previous report period and were reported in PWA-2518, pages 23 and 24. During this report period, the specimen which withstood 10^7 cycles at 57,000 psi with no cracking or spalling of the coating occurring was tested in the fatigue specimen inspection rig. Examination of the specimen at 1500°F revealed no areas of coating separation (see Figure 7). Consequently, on the basis of these and previous results, it may be concluded that calcium titanate coatings on AISI-310 stainless steel have adequate bond strength to withstand 10^7 cycles of alternate bending at the run-out fatigue stress level for the substrate without cracking, spalling, or separating from the substrate.

B. Iron Titanate on AISI-310 Stainless Steel

1. Long-Term Testing

The AISI-310 stainless steel tube coated with a 4-mil thick layer of iron titanate has now accrued 5300 hours of testing at 1350°F in the long-term total hemispherical emittance rig. The emittance obtained during the first 2500 hours was about 0.89, after which it dropped slightly to 0.88 where it has remained. The emittance values obtained for this coating to date are shown in Figure 8. The vacuum maintained has been about 2×10^{-8} mm Hg as shown in Figure 9.

The specimen has been thermally cycled 18 times during the report period, making a total of 24 thermal shocks since the beginning of short-term testing for this specimen.

2. Adherence Testing

Fatigue tests were conducted to determine the bond strength of iron titanate to AISI-310 stainless steel. Westinghouse round-bar fatigue specimens were fabricated from AISI-310 stainless steel bar stock and coated with 4-mil thick coatings of iron titanate (see Figure 10). Uncoated specimens were also fabricated to determine the run-out fatigue strength of the substrate material.

The results for the uncoated specimens are shown in Figure 11 and indicate that the run-out stress is 50,000 to 55,000 psi. The results for the coated specimens were similar, as shown in Figure 12. All of

the coated specimens failed through fracture of the substrate. No failures resulted from spalling or cracking. A typical failed specimen is shown in Figure 13.

The specimen which withstood 10^7 cycles at 52,000 psi with no cracking or spalling of the coating occurring was tested in the fatigue specimen inspection rig to determine if any separation of the coating had occurred. No dark areas were evident, indicating that separation had not occurred. The specimen at 1500°F is shown in Figure 14.

The adherence testing conducted on iron-titanate coatings on AISI-310 stainless steel have demonstrated that the coating has adequate bond strength.

C. Iron Titanate on Columbium-1 Percent Zirconium

1. Long-Term Testing

The long-term testing of a columbium-1 percent zirconium tube coated with a 4-mil thick layer of iron titanate was continued. During the report period, 4300 hours of additional testing were accumulated for a total of 6250 hours at 1700°F since the beginning of the program.

At the start of the test, the emittance was 0.88, but it dropped to 0.85 between 600 and 1800 hours, and has remained relatively constant at about 0.85 since then. The emittance values obtained are shown in Figure 15.

Small fluctuations in the vacuum occurred during the test as a result of slight leaks, but at no time did the pressure exceed 10^{-7} mm Hg. The vacuum maintained is shown in Figure 16.

This specimen has been thermally cycled a total of 29 times, with 19 cycles conducted during the report period. No adverse effects have occurred.

2. Adherence Testing

Fatigue tests were conducted to determine the bond strength of iron titanate to columbium-1 percent zirconium. Fifteen specimens were prepared, seven with coatings and eight without coatings. A typical coated specimen is shown in Figure 17.

Testing of the uncoated specimens indicated that the run-out fatigue strength of columbium-1 percent zirconium is 30,000 to 33,000 psi (see Figure 18). The coated specimens were found to have a run-out

fatigue strength of 35,000 psi, about the same as that for the uncoated specimens. These results are shown in Figure 19. In all cases, failure was the result of fracture of the substrate rather than spalling or cracking of the coating. A typical failed specimen is shown in Figure 20.

A specimen which withstood a stress of 35,000 psi for 10^7 cycles with no cracking or spalling of the coating occurring was heated to 1500°F in vacuum and examined for evidence of coating separation. As shown in Figure 21, no indication of separation was evident, indicating that the bond strength between iron titanate and columbium-1 percent zirconium is excellent.

D. Aluminum Oxide - Aluminum Titanate on Columbium-1 Percent Zirconium

1. Material Analysis and Specimen Preparation

An aluminum oxide-aluminum titanate composition was obtained from the Zirconium Corporation of America. This composition was prepared from 88 weight percent aluminum oxide and 12 weight percent titanium oxide. Emission spectrographic analysis detected the following impurities: 0.5% Fe, 0.1% Si, 0.6% Mg, and a trace of Mn.

The composition was applied to columbium-1 percent zirconium tubes by plasma-arc spraying. The particle size distribution of the powder used is shown in Table 1. Argon was used as both the arc gas and the carrier gas with flow rates of 45 and 40 cubic feet per hour, respectively. The current was 600 amperes. The resulting coatings were 4 mils thick. After spraying, spectrographic analysis of scrapings from the tube indicated that the following impurities were present: 0.05% Fe, 0.1% Si, 0.04% Mg, and a trace of Mn.

TABLE 1
Particle Size Distribution of Aluminum
Oxide-Aluminum Titanate Powder

| <u>Particle Size (Microns)</u> | <u>Cumulative Weight Percent</u> |
|------------------------------------|--------------------------------------|
| 63 | 0 |
| 50 | 17.0 |
| 40 | 71.0 |
| 32 | 100.0 |

2. Short-Term Testing

One of the specimens was tested in the short-term endurance rig for 268 hours at 1700°F in a vacuum of not less than 10^{-8} mm Hg. The emittance was about 0.85 throughout the test. After testing, the coating texture was unchanged and the test chamber showed no indications of coating volatilization.

On the basis of these results, this specimen was selected for long-term endurance testing.

3. Long-Term Testing

The specimen subjected to short-term testing was reinstrumented and installed in a long-term endurance rig. To date, 1000 hours of testing at 1700°F in a vacuum of 10^{-7} mm Hg (see Figure 22) has been accumulated. The emittance was about 0.85 for the first 300 hours of testing, and, since then, it has dropped slowly to the present value of 0.83. The emittance values obtained to date are shown in Figure 23.

The specimen was thermally cycled after initial heating, after 100, 200, 300, 400, and 500 hours of testing, and subsequently once each week. To date the specimen has been cycled 9 times with no evidence of adverse effects.

E. Stabilized Titanium Oxide Composition on Columbium-1 Percent Zirconium

1. Material Analysis and Specimen Preparation

A proprietary stabilized titanium oxide composition designated as Y692 was obtained from the Zirconium Corporation of America. The emission spectrographic analysis detected the presence of 0.01% Mg, 0.02% Si, 0.01% Fe, and trace amounts of Al, Cu, and Ni.

Specimens were prepared by plasma-arc spraying columbium-1 percent zirconium tubes with 4-mil thick layers of the material. The particle size distribution of the powder used is shown in Table 2. Argon was used for both the arc gas and the carrier gas with flow rates of 50 and 40 cubic feet per hour, respectively. The current used was 700 amperes. Spectrographic analysis after spraying detected the presence of 0.02% Si, 0.3% Al, and trace amounts of Fe, Mg, and Mn.

TABLE 2

Particle Size Distribution of
Stabilized Titanium Oxide Composition

| <u>Particle Size (Microns)</u> | <u>Cumulative Weight Percent</u> |
|------------------------------------|--------------------------------------|
| 63 | 36.0 |
| 50 | 55.0 |
| 40 | 75.0 |
| 32 | 99.0 |
| 25 | 100.0 |

2. Short-Term Testing

Two specimens were tested in the short-term endurance rig. The first test was run for 294 hours at 1700°F in a vacuum of 10^{-8} mm Hg. The emittance throughout the test was about 0.87. The specimen was thermally cycled after initial heating and after 100 and 250 hours of testing, but examination of the specimen after testing detected no cracking, spalling, or other changes in the coating, nor did the test chamber show any evidence of coating volatilization.

Although the first test indicated that the coating was suitable for long term testing, a second test was conducted to verify the results since this material had not been tested previously. During the second test, the emittance again was 0.87. The specimen was thermally cycled after initial heating and after 100 and 240 hours of testing. In addition, a malfunction of the voltage regulator caused the specimen to be overheated by 250°F for two hours after 260 hours of testing. No adverse effects were visible.

3. Long-Term Testing

The first specimen tested in short-term rig for 294 hours was installed in a long-term rig for further evaluation. After a short period in the long-term rig, localized coating separation occurred and the emittance dropped to about 0.80. The areas of separation appeared darker than the adjacent areas as shown in Figure 24.

In order to determine if the coating separation was a characteristic of the coating material or only a peculiarity of the particular specimen, a second specimen which had not been subjected to short-term testing was

installed in a long-term rig and tested at 1700°F in a vacuum of 10^{-8} mm Hg. For the first 300 hours, the emittance remained between 0.86 and 0.87. But after 300 hours, evidence of coating separation was observed and the emittance decreased. The test was continued for another 700 hours to determine the amount of separation that would occur and its effect on the emittance. At the end of this period, extensive separation had occurred, and the emittance had dropped to 0.78, as shown in Figure 25.

Since coating separation had occurred on both specimens after about 300 hours of testing, this material was rejected for space radiator applications at 1700°F.

F. Zirconium Titanate on Columbium-1 Percent Zirconium

1. Material Analysis and Specimen Preparation

Zirconium titanate powder was obtained from the Zirconium Corporation of America for emittance testing. X-ray diffraction analysis indicated that $ZrTiO_4$ was the only phase present, and spectrographic analysis detected the presence of 0.3% Si, 0.01% Mg, 0.3% Al, 0.6% Hf, and traces of Fe and Mn. The particle size distribution of the powder is shown in Table 3.

TABLE 3
Particle Size Distribution of
Zirconium Titanate Powder

| <u>Particle Size (Microns)</u> | <u>Cumulative Weight Percent</u> |
|------------------------------------|--------------------------------------|
| 63 | 32.0 |
| 50 | 84.0 |
| 40 | 93.0 |
| 32 | 95.0 |
| 25 | 96.0 |
| 20 | 99.0 |
| 17 | 100.0 |

Several specimens were prepared by plasma-arc spraying four-mil thick coatings of zirconium titanate on columbium-1 percent zirconium tubes. Argon was used as both the arc gas and the carrier gas with flow rates of 52 and 40 cubic feet per hour, respectively. The current used was 350 amperes. Scrapings from the tubes were analyzed by

X-ray diffraction and spectrographic analysis. X-ray diffraction analysis indicated that zirconium titanate was the only phase present, and spectrographic analysis detected the presence of 0.07% Si, 0.2% Al, 1.0% Hf, and traces of Fe, Mg, and Mn.

2. Short-Term Testing

One of the specimens was tested in the short-term endurance rig at 1700°F in a vacuum of 10^{-8} mm Hg for 312 hours. At the start of the test, the emittance was 0.85, but it gradually dropped to 0.82 by the end of the 312 hours. This material, therefore, was rejected for long-term endurance testing because of its inability to maintain an emittance of 0.85 or better.

G. Barium Titanate Composition on Columbium - 1 Percent Zirconium

1. Material Analysis and Specimen Preparation

A composition containing 88 percent barium titanate, 9.4 percent barium zirconate, and 2.6 percent manganese dioxide was obtained from the Zirconium Corporation of America. X-ray diffraction detected only the major constituent, barium titanate. Spectrographic analysis revealed the presence of 0.04% Si, 0.02 % Mg, 0.1% Al, 0.05% Hf, and a trace of Fe. The particle size distribution of the powder is shown in Table 4.

TABLE 4

Particle Size Distribution of
Barium Titanate Composition

| <u>Particle Size</u> <u>(Microns)</u> | <u>Cumulative</u> <u>Weight Percent</u> |
|--|--|
| 63 | 0 |
| 50 | 25.0 |
| 40 | 42.0 |
| 32 | 52.0 |
| 25 | 65.0 |
| 20 | 76.0 |
| 17 | 85.0 |
| 14 | 91.0 |
| 12 | 95.0 |
| 9 | 98.0 |
| 7 | 99.0 |
| 6 | 100.0 |

Specimens for emittance testing were prepared by plasma arc spraying 4-mil thick coatings on columbium - 1 percent zirconium tubes. Argon was used for both the arc gas and the carrier gas with flow rates of 45 and 40 cubic feet per hour, respectively. The current used was 600 amperes. X-ray diffraction analysis after spraying detected only barium titanate. Spectrographic analysis showed 0.02% Si, 0.1% Al, 0.1% Hf, and traces of Fe and Mn to be present as impurities.

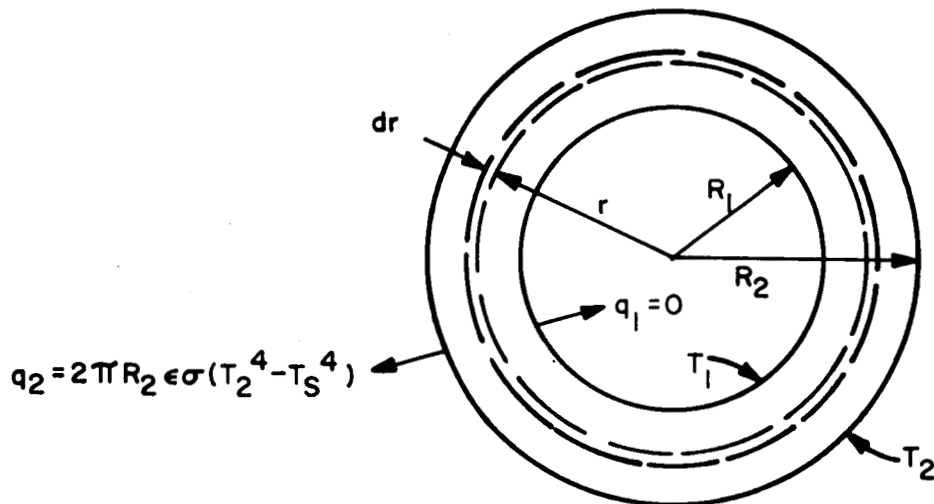
2. Short-Term Testing

One of the specimens was installed in the short-term endurance rig and tested at 1700°F in a vacuum of 10^{-9} mm Hg. Initially, the emittance was 0.80, but it dropped to 0.71 after 97 hours of testing and the test was terminated. The emittance of this coating is too low to warrant additional testing.

V. ANALYTICAL STUDIES

During the report period, the temperature difference between the inner and outer surfaces of cylindrical tubes which are resistance heated in vacuum was determined analytically. This information was required because temperature measurements are often made using thermocouples on the outer surface of a specimen and an optical pyrometer which is sighted through a small hole in the specimen to read the inner temperature.

The temperature difference was calculated on the assumption that heat generation in the metal occurs at a uniform rate and that the temperature does not vary with axial location. The notation used for the analysis is shown in the sketch below.



Assuming heat generation at the rate of g per unit volume, the one-dimensional heat balance on the differential element $2\pi r dr$ is:

$$r \frac{d^2 t}{dr^2} + \frac{dt}{dr} + \frac{gr}{K} = 0 \quad (1)$$

In addition, the following boundary conditions exist:

$$\text{at } r = R_2, \quad -KA \frac{dt}{dr} = q_2 \quad (2)$$

$$\text{at } r = R_1, \quad t = T_1 \quad (3)$$

Finally, the heat generation rate g may be expressed in terms of the net heat lost as:

$$g = \frac{2 \pi R_2 \epsilon \sigma (T_2^4 - T_s^4)}{\pi (R_2^2 - R_1^2)} \quad (4)$$

Integration of equation (1) yields

$$t = \frac{-gr^2}{4K} + C_1 \ln r + C_2 \quad (5)$$

where

$$C_1 = \frac{1}{2K} \left(g R_2^2 - \frac{q_2}{\pi} \right) \quad (6)$$

$$C_2 = T_1 + \frac{g R_1^2}{4K} - C_1 \ln R_1 \quad (7)$$

because of equations (2) and (3).

Substituting equations (4), (6), and (7) into equation (5) and evaluating at $r = R_2$ yields:

$$T_2 = \alpha (T_2^4 - T_s^4) + T_1 \quad (8)$$

where

$$\alpha = \frac{R_2 \epsilon \sigma}{K} \left(\frac{R_1^2}{R_2^2 - R_1^2} \ln \frac{R_2}{R_1} - \frac{1}{2} \right) \quad (9)$$

Equation 8 has been plotted in Figures 26 and 27 for AISI-310 stainless steel and columbium-1 percent zirconium, respectively, for a sink temperature of 70°F. As shown, the temperature drop for either material never exceeds 0.5°F at the temperatures at which they are used, and, therefore, may be neglected.

VI. CONCLUSIONS

The work conducted to date indicates that calcium titanate and iron titanate are suitable materials for space radiator applications. The specimens tested with these coatings have revealed the properties tabulated below.

A. Calcium Titanate on AISI-310 Stainless Steel

1. Total hemispherical emittance of about 0.90 for 6300 hours at 1350°F in a vacuum of 10^{-8} mm Hg
2. Ability to withstand thermal cycling from 1350°F
3. Ability to maintain good adherence when subjected to fatigue testing for 10^7 cycles at 120 cps at stress levels up to 55,000 psi (the run-out fatigue strength of AISI-310 stainless steel)

B. Iron Titanate on AISI-310 Stainless Steel

1. Total hemispherical emittance of about 0.88 for 5300 hours at 1350°F in a vacuum of 10^{-8} mm Hg
2. Freedom from adverse effects when subjected to thermal cycling from 1350°F
3. Ability to maintain good adherence when subjected to fatigue testing for 10^7 cycles at 120 cps at stress levels up to 55,000 psi (the run-out fatigue strength of AISI-310 stainless steel)

C. Iron Titanate on Columbium-1 Percent Zirconium

1. Total hemispherical emittance of about 0.85 for 6250 hours at 1700°F in a vacuum of 10^{-8} mm Hg
2. Ability to withstand thermal cycling from 1700°F
3. Ability to maintain good adherence when subjected to fatigue testing for 10^7 cycles at 120 cps at a stress level up to 35,000 psi (the run-out fatigue strength of columbium-1 percent zirconium)

VII. FUTURE WORK

The four long-term total hemispherical emittance tests now underway will be continued for up to 10,000 hours.

Work will be begun on evaluating the compatibility, emittance stability, and adherence of high emittance coatings applied to beryllium substrates. Three high emittance coatings will be used with tests being conducted at 800°F and 1400°F in vacuum for periods up to 1000 hours.

APPENDIX A

Figures

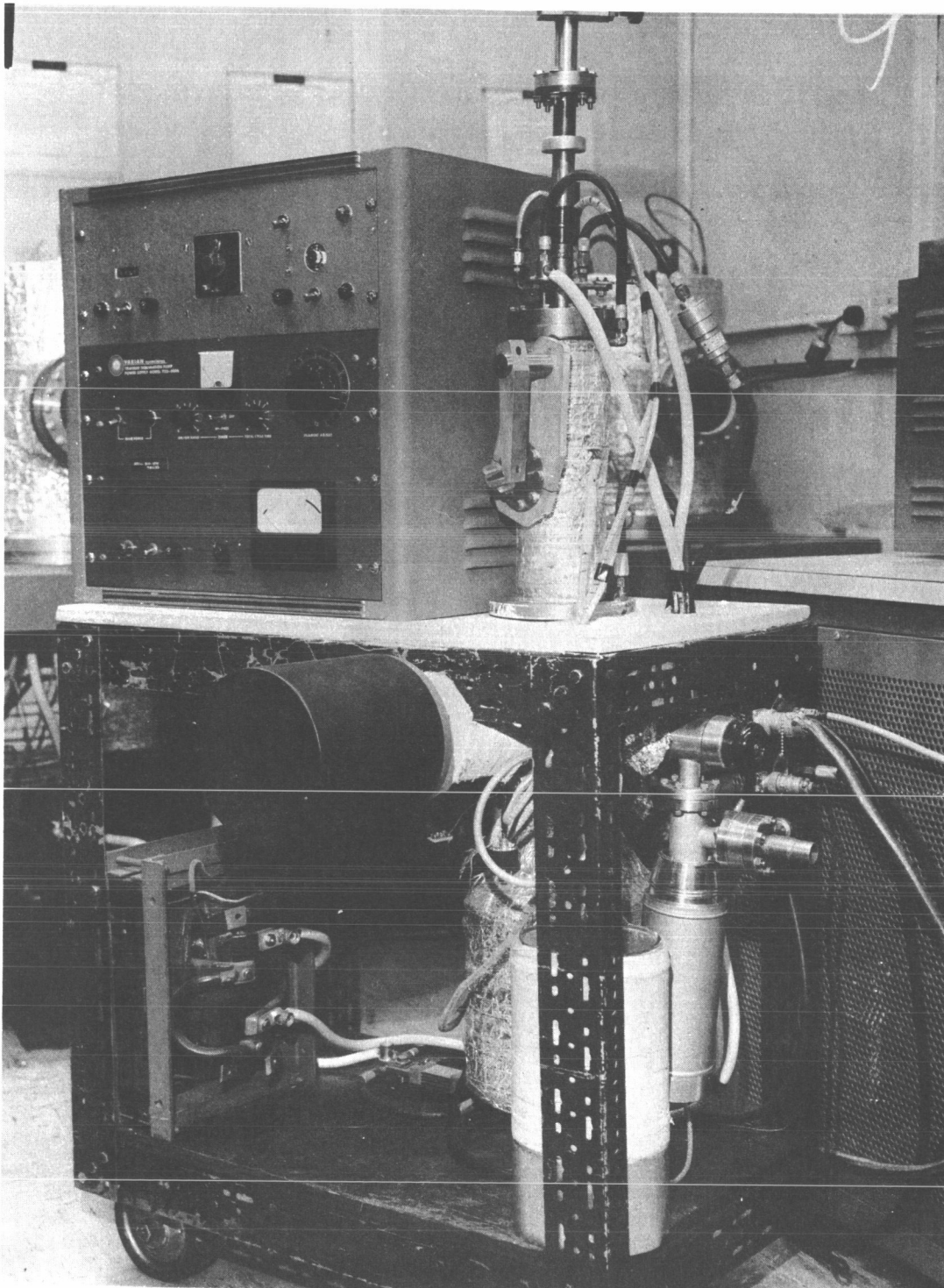


Figure 1 - Short Term Endurance Total
Hemispherical Emittance Rig

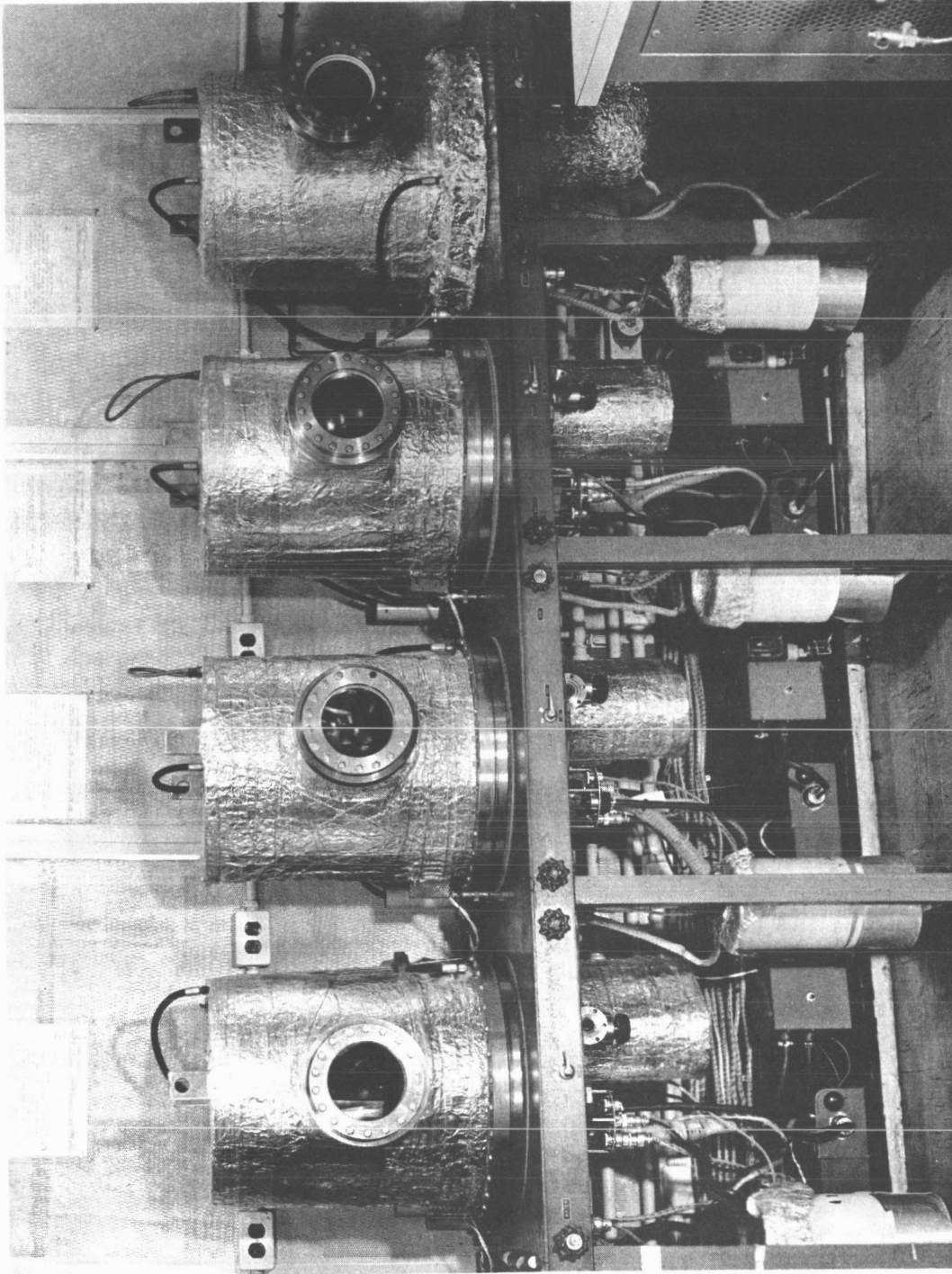


Figure 2 - Long-Term Endurance Total Hemispherical Emittance Rigs

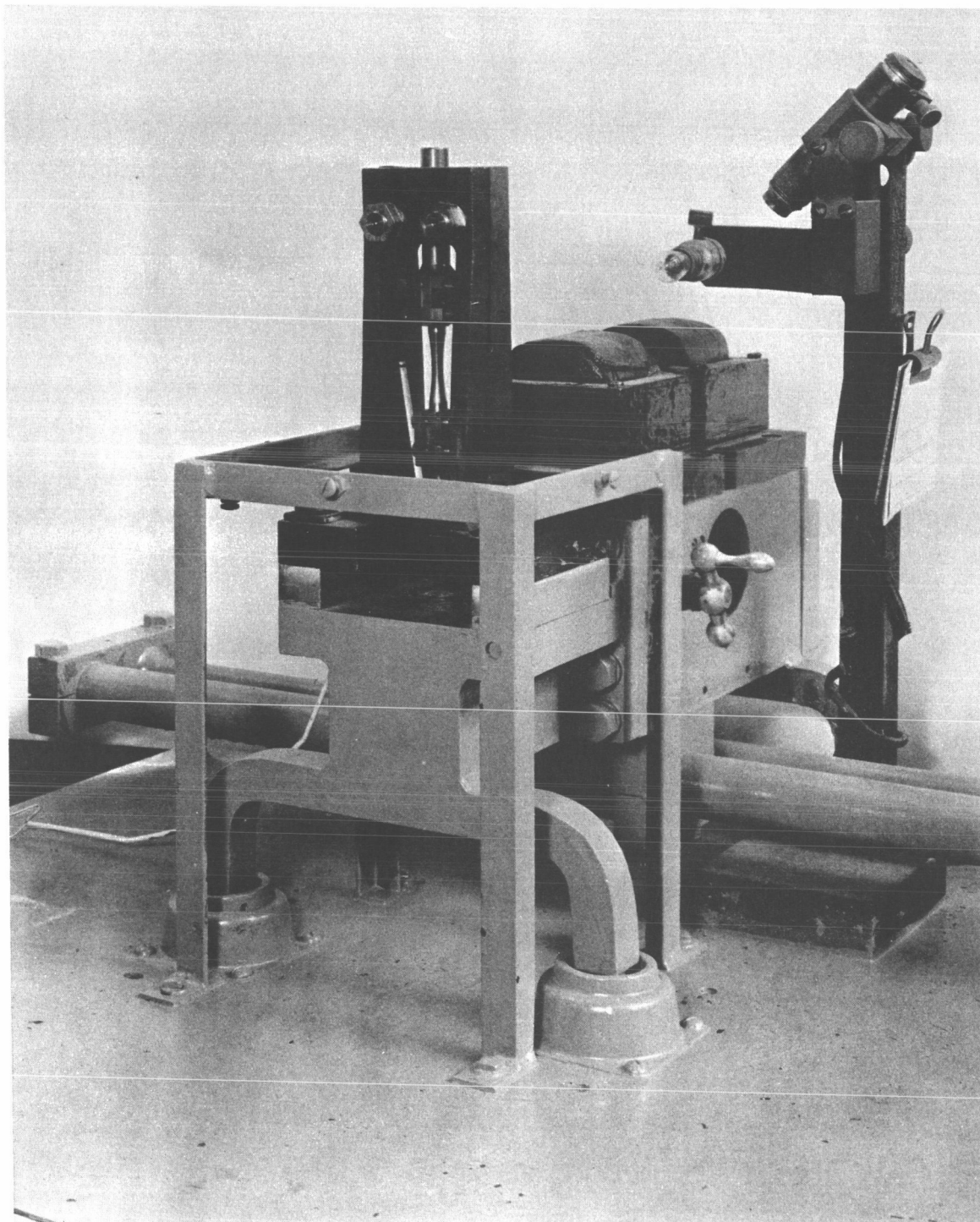


Figure 3 - Westinghouse Vibration Fatigue Apparatus

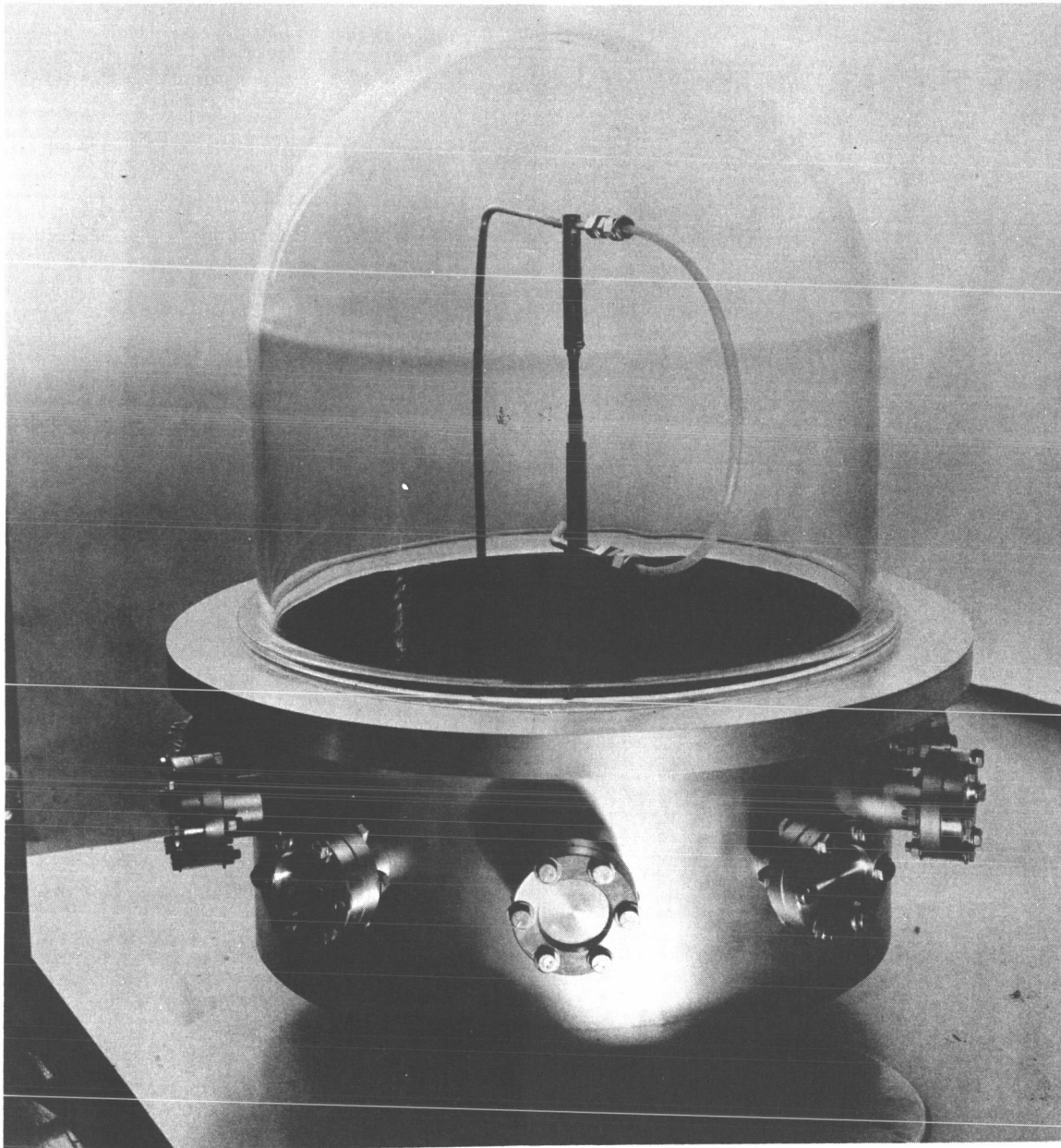


Figure 4 - Fatigue Specimen Inspection Rig

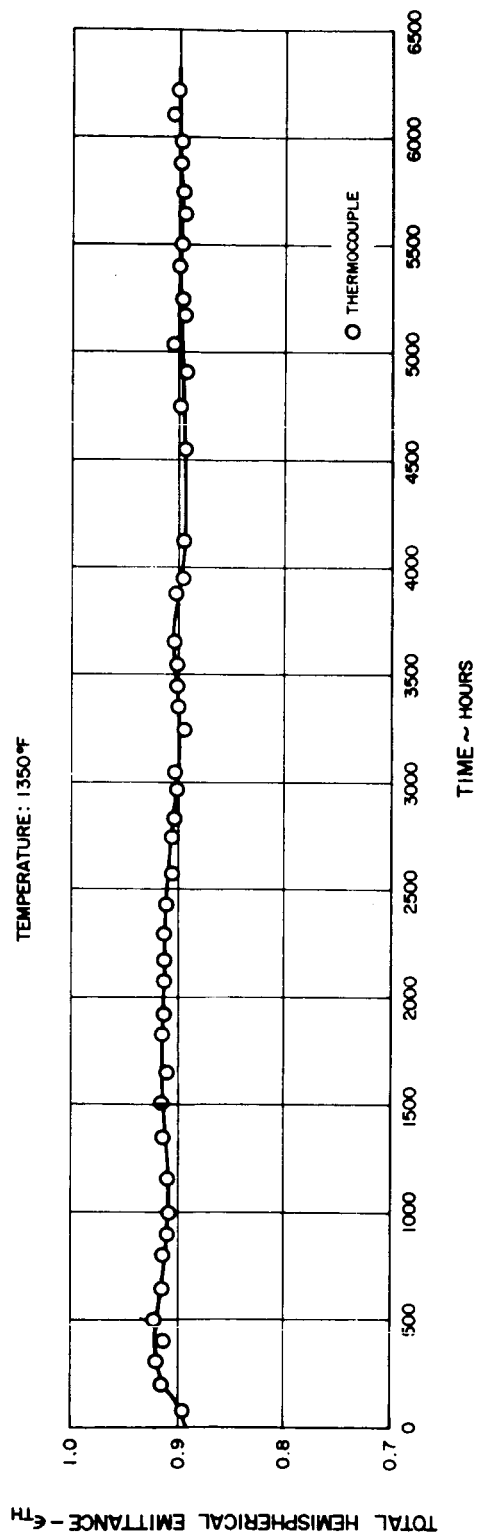


Figure 5 - Total Hemispherical Emittance of AISI-310 Stainless Steel Tube Coated With Calcium Titanate

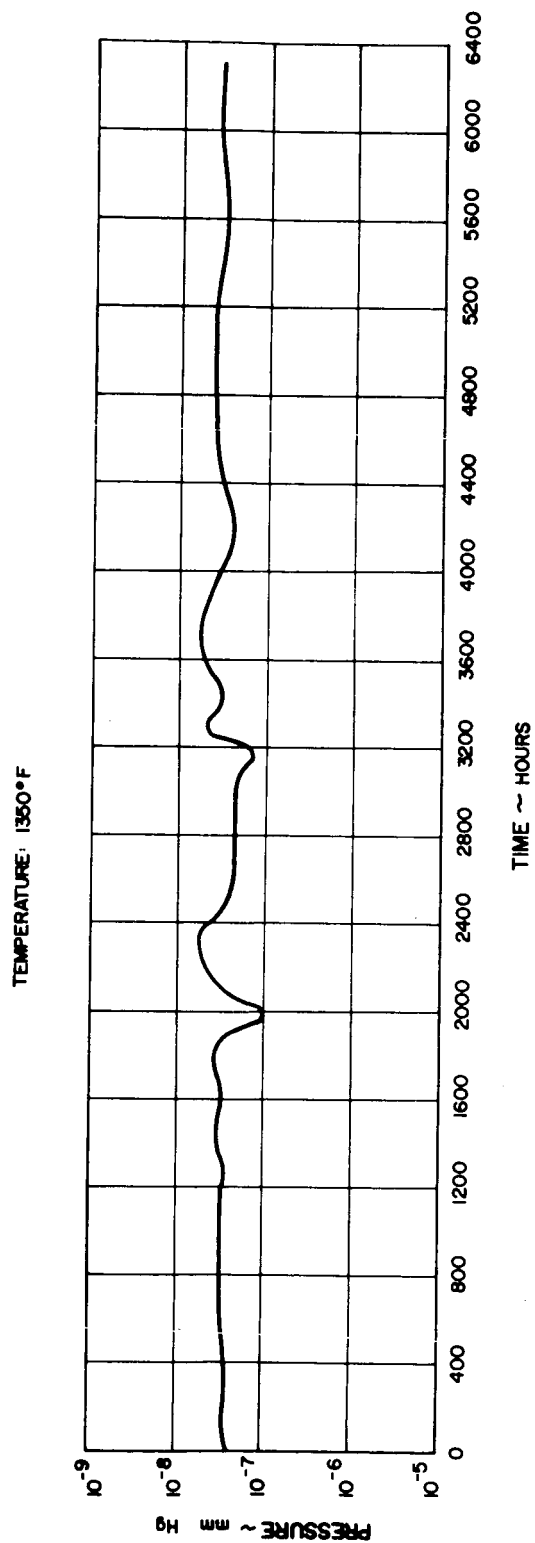


Figure 6 - Chamber Pressure During Testing of AISI-310 Stainless Steel Tube
Coated With Calcium Titanate

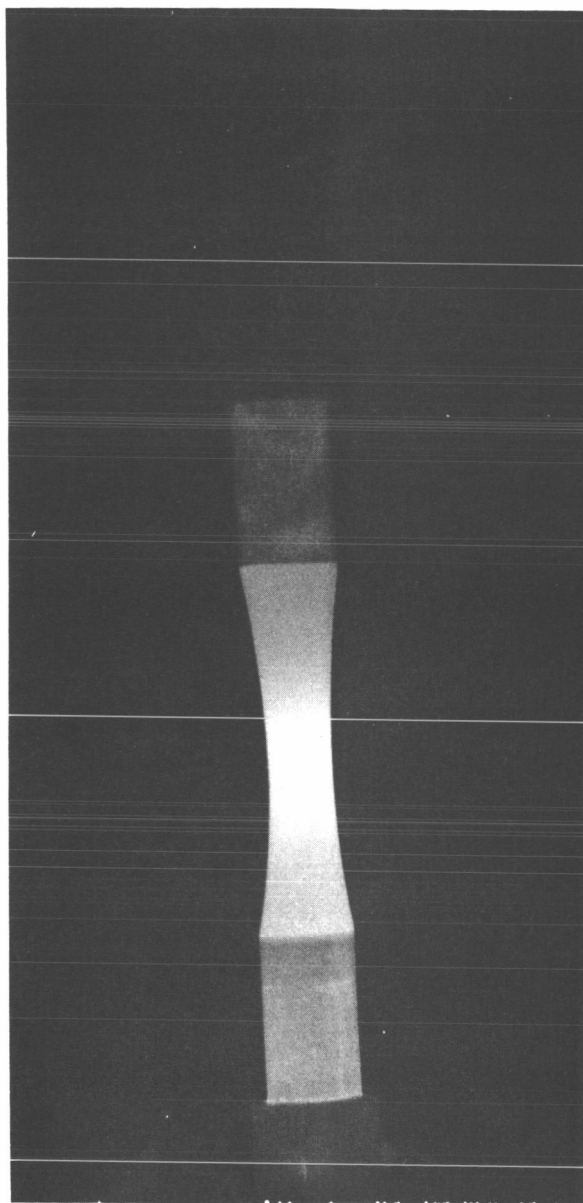


Figure 7 - AISI-310 Stainless Steel Fatigue Specimen Coated With Calcium Titanate and Heated to 1500°F for Coating Separation Inspection

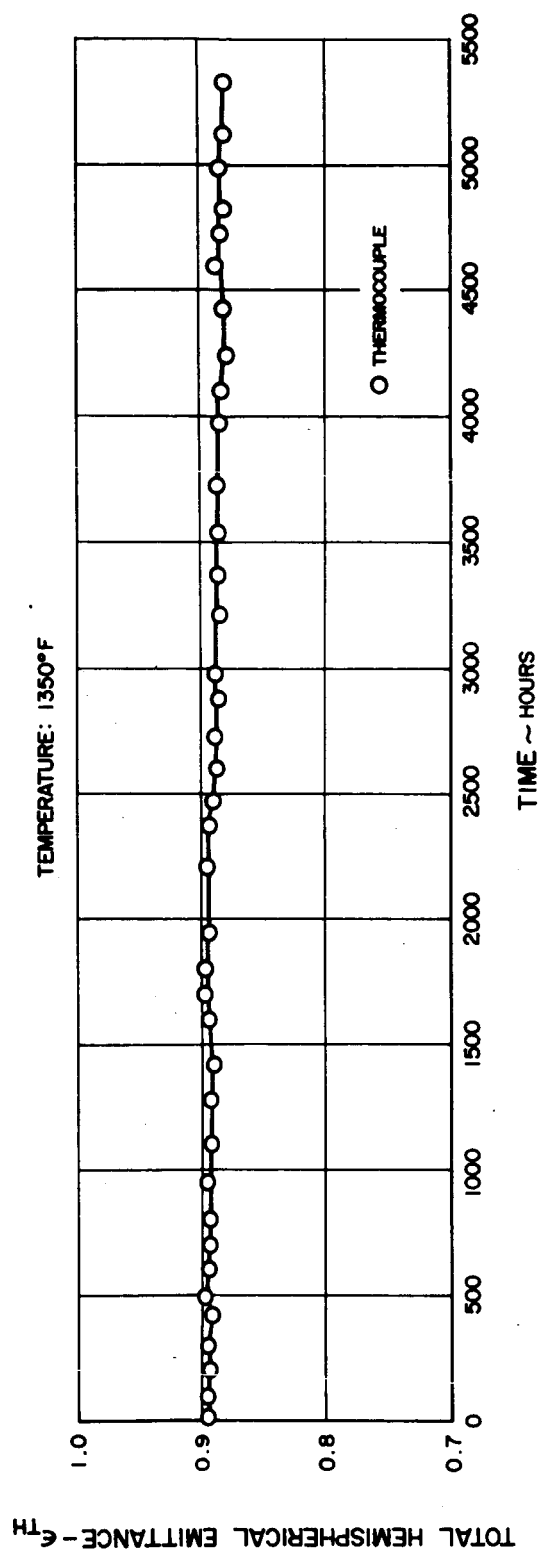


Figure 8 - Total Hemispherical Emittance of AISI-310 Stainless Steel Tube
Coated With Iron Titanate

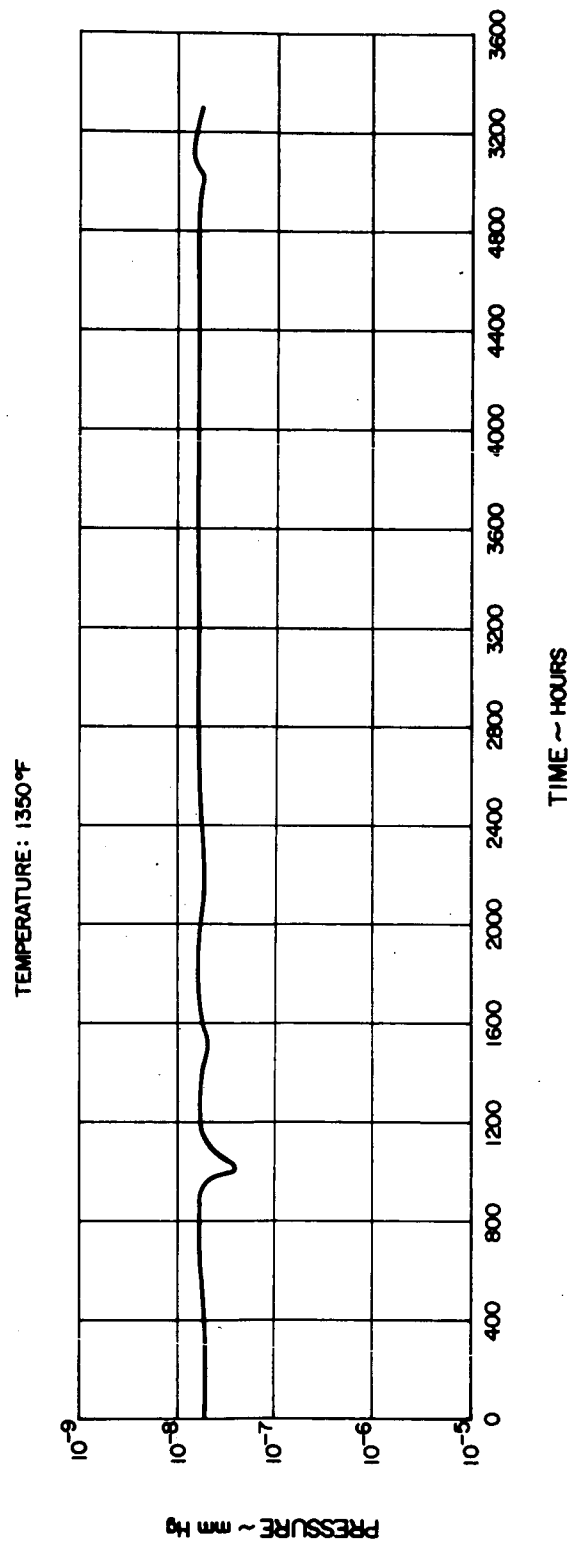


Figure 9 - Chamber Pressure During Testing of AISI-310 Stainless Steel Tube
Coated With Iron Titanate

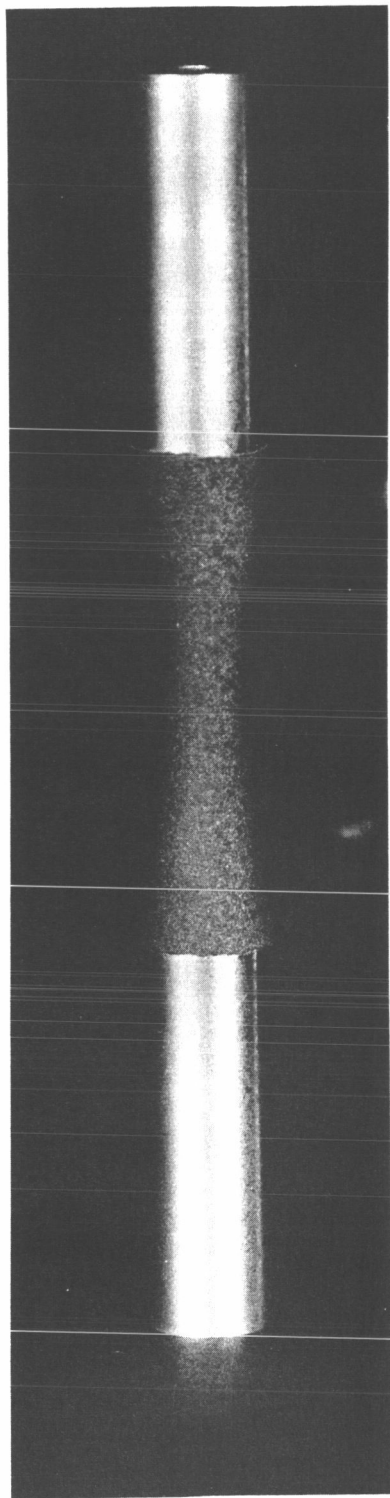


Figure 10 - AISI-310 Stainless Steel Fatigue Specimen
Coated With 4-Mil Thick Layer of Iron Titanate

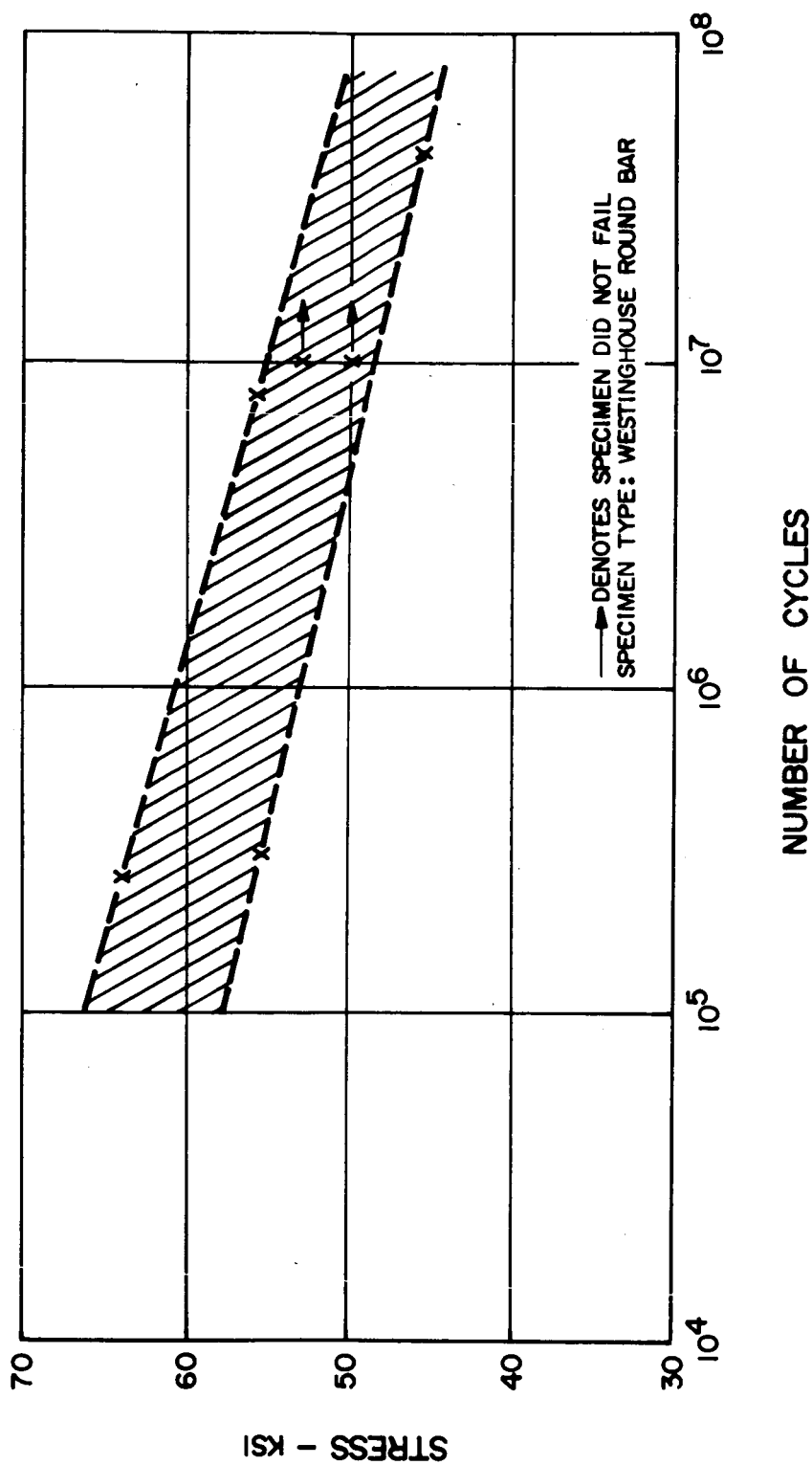


Figure 11 - Fatigue Test Results Obtained at Room Temperature for AISI-310 Stainless Steel

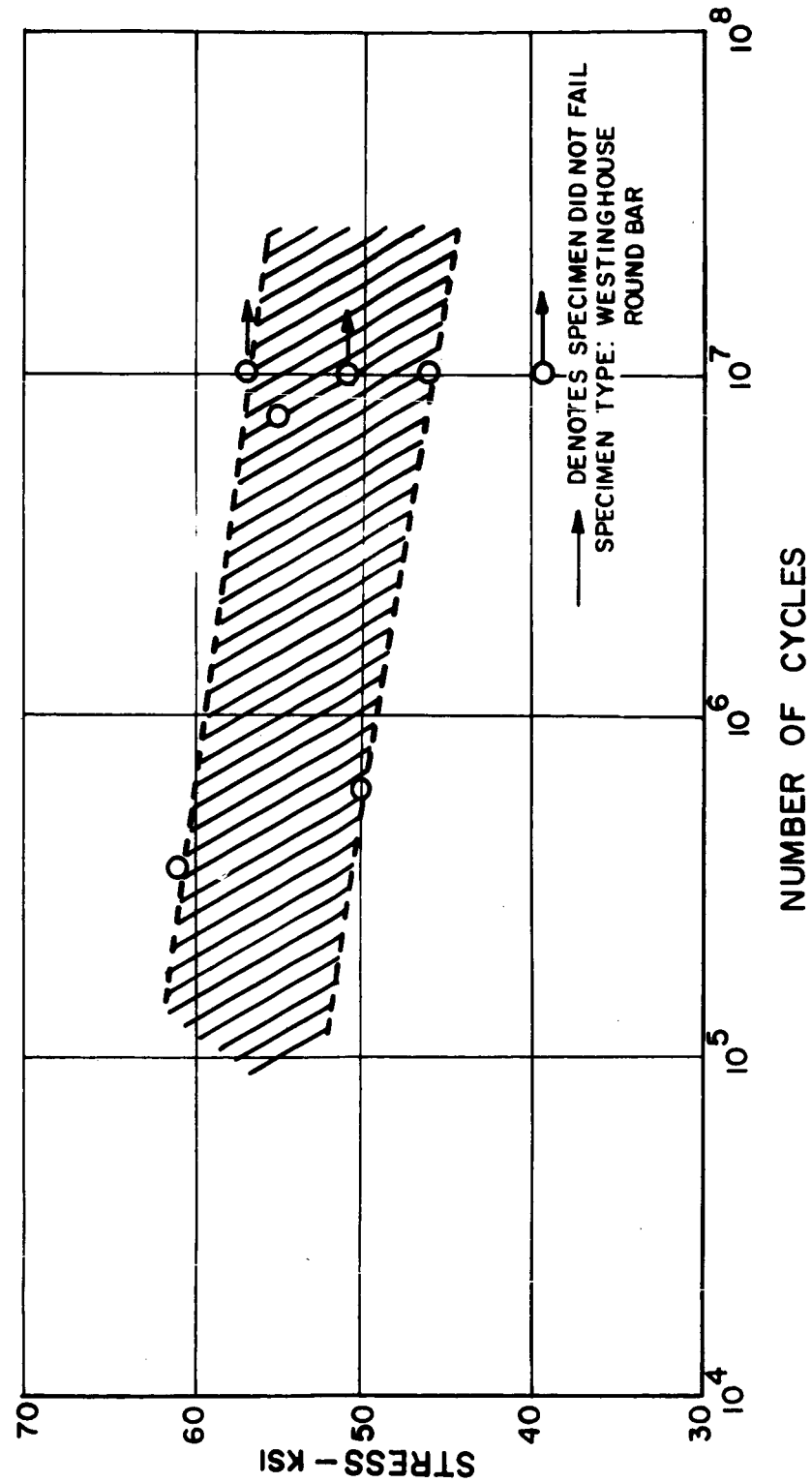


Figure 12 - Fatigue Test Results Obtained at Room Temperature for AISI-310
Stainless Steel Coated with Iron Titanate

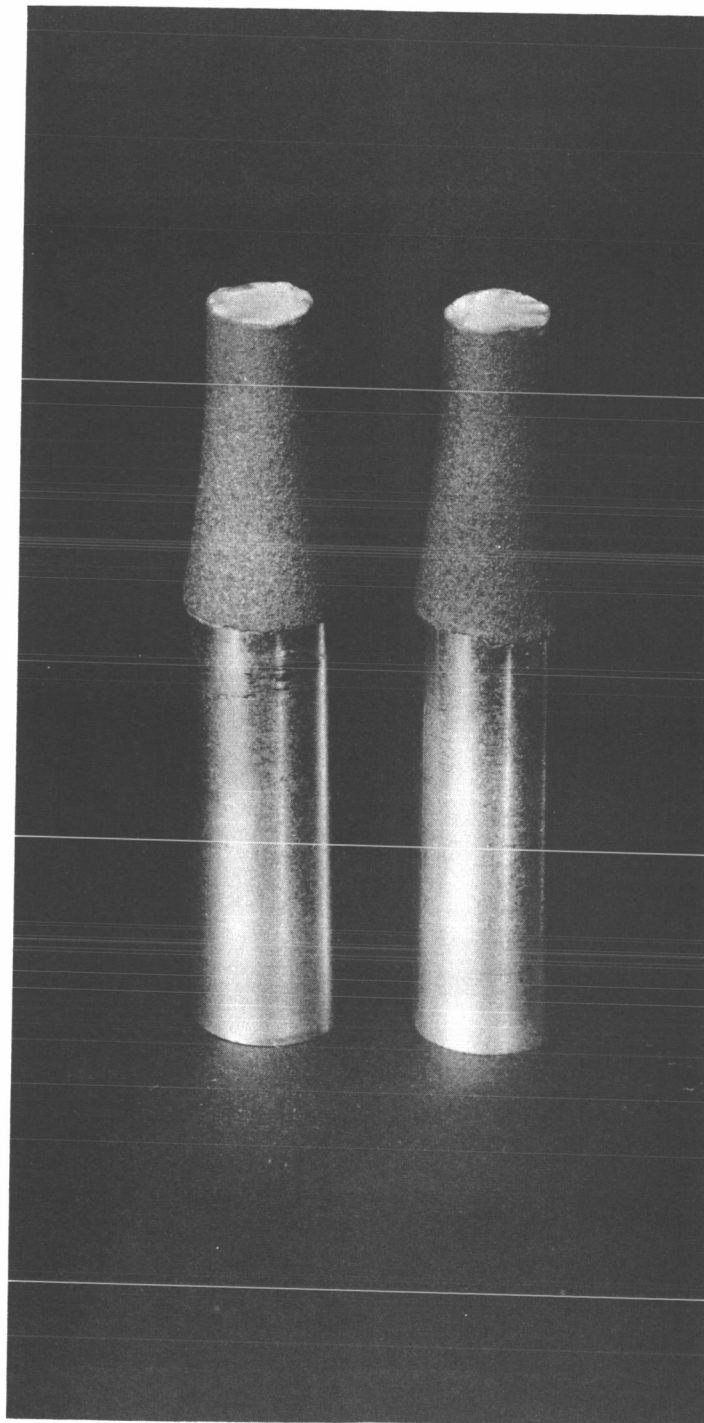


Figure 13 - Fractured AISI-310 Stainless Steel Fatigue Specimen Coated With Iron Titanate

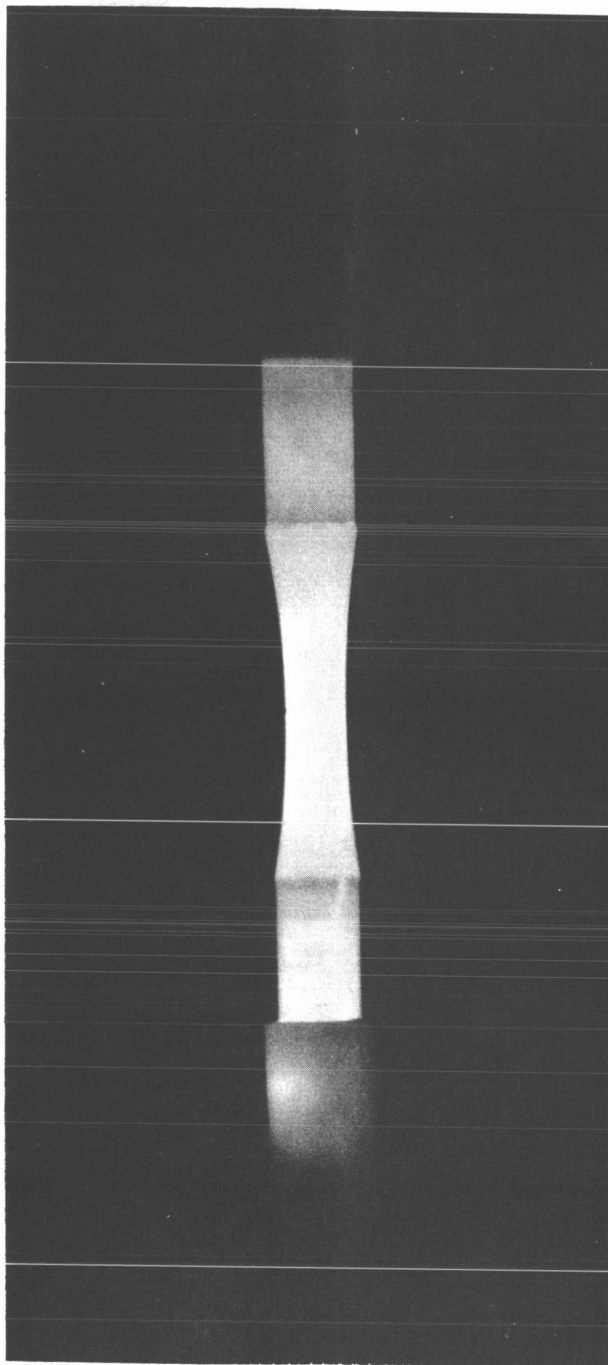


Figure 14 - AISI-310 Stainless Steel Fatigue Specimen Coated With Iron Titanate and Heated to 1500 °F for Coating Separation Inspection

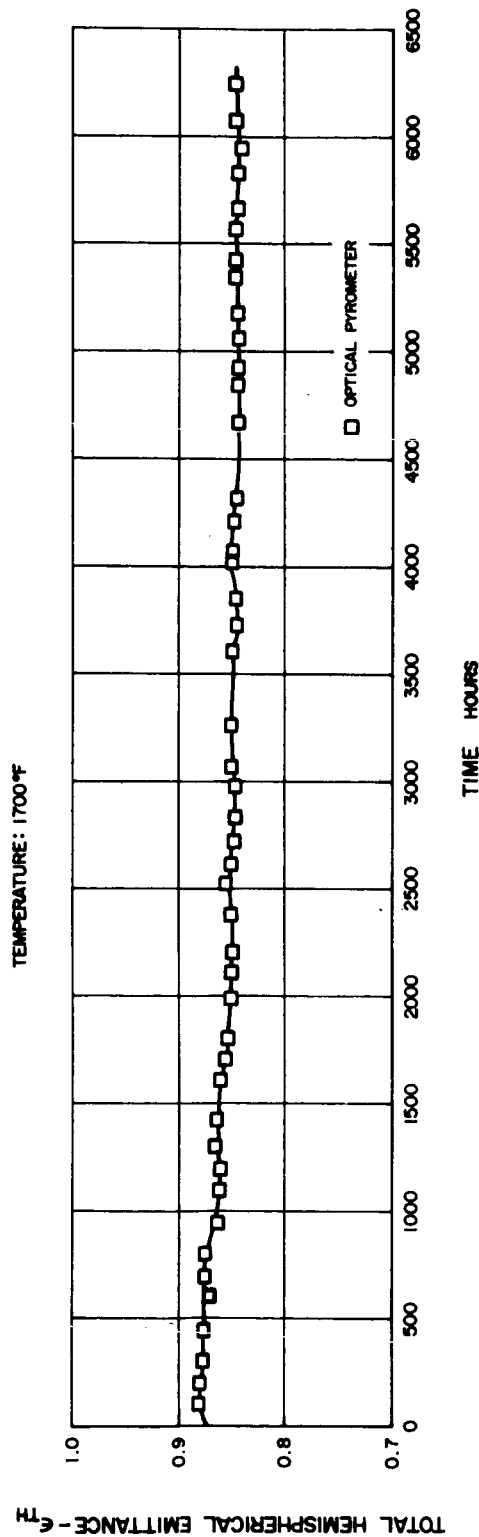


Figure 15 - Total Hemispherical Emittance of Columbium-1 Percent Zirconium Tube
Coated With Iron Titanate

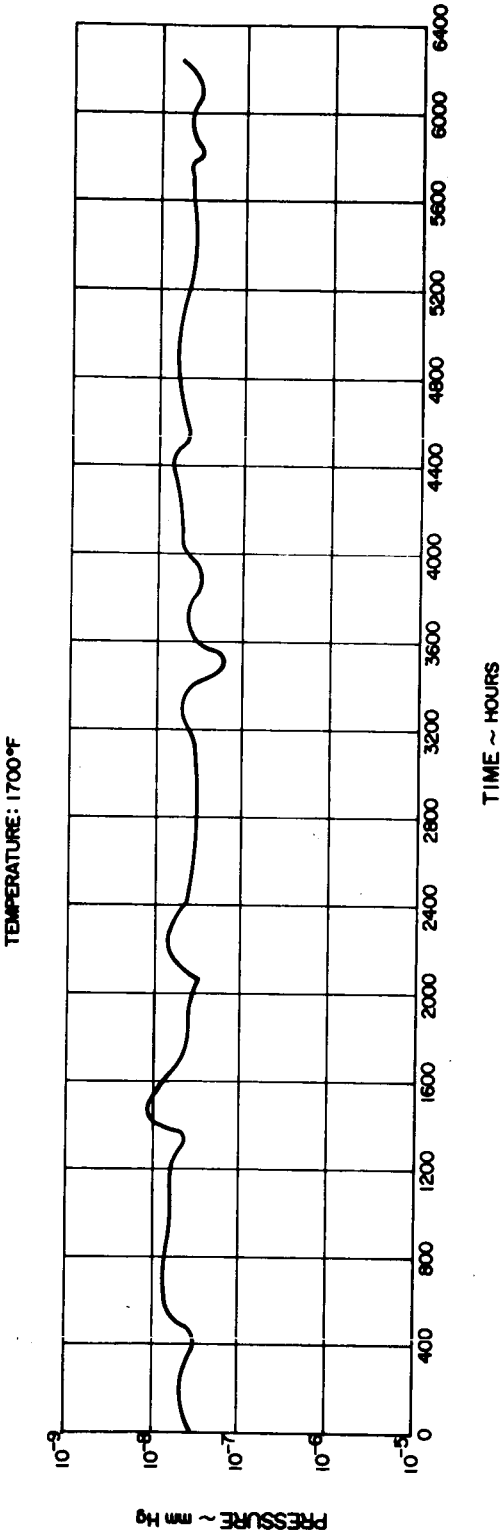


Figure 16 - Chamber Pressure During Testing of Columbium-1 Percent Zirconium Tube Coated With Iron Titanate

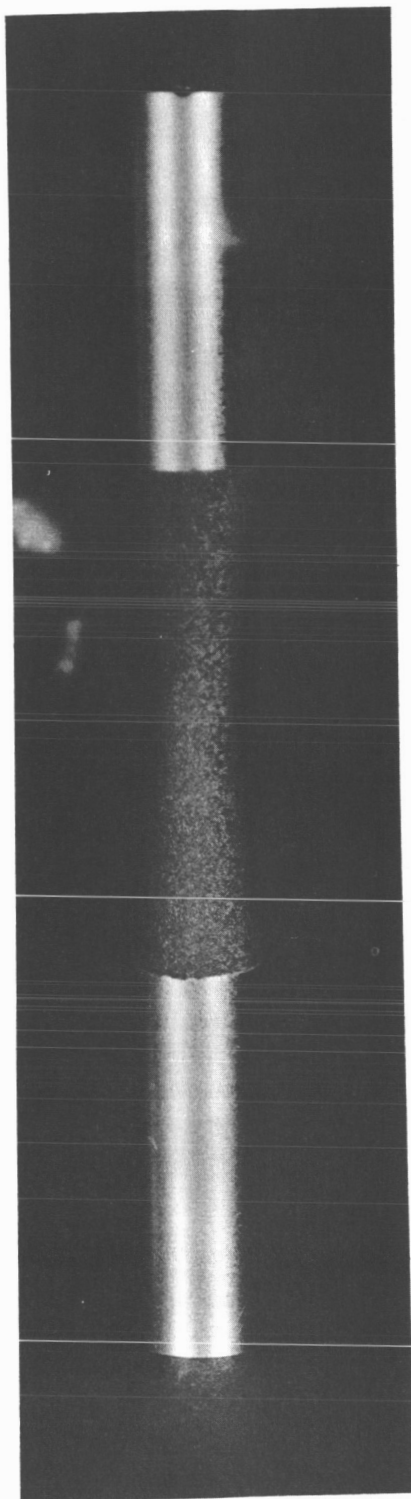


Figure 17 - Columbium-1 Percent Zirconium Fatigue
Specimen Coated With Iron Titanate

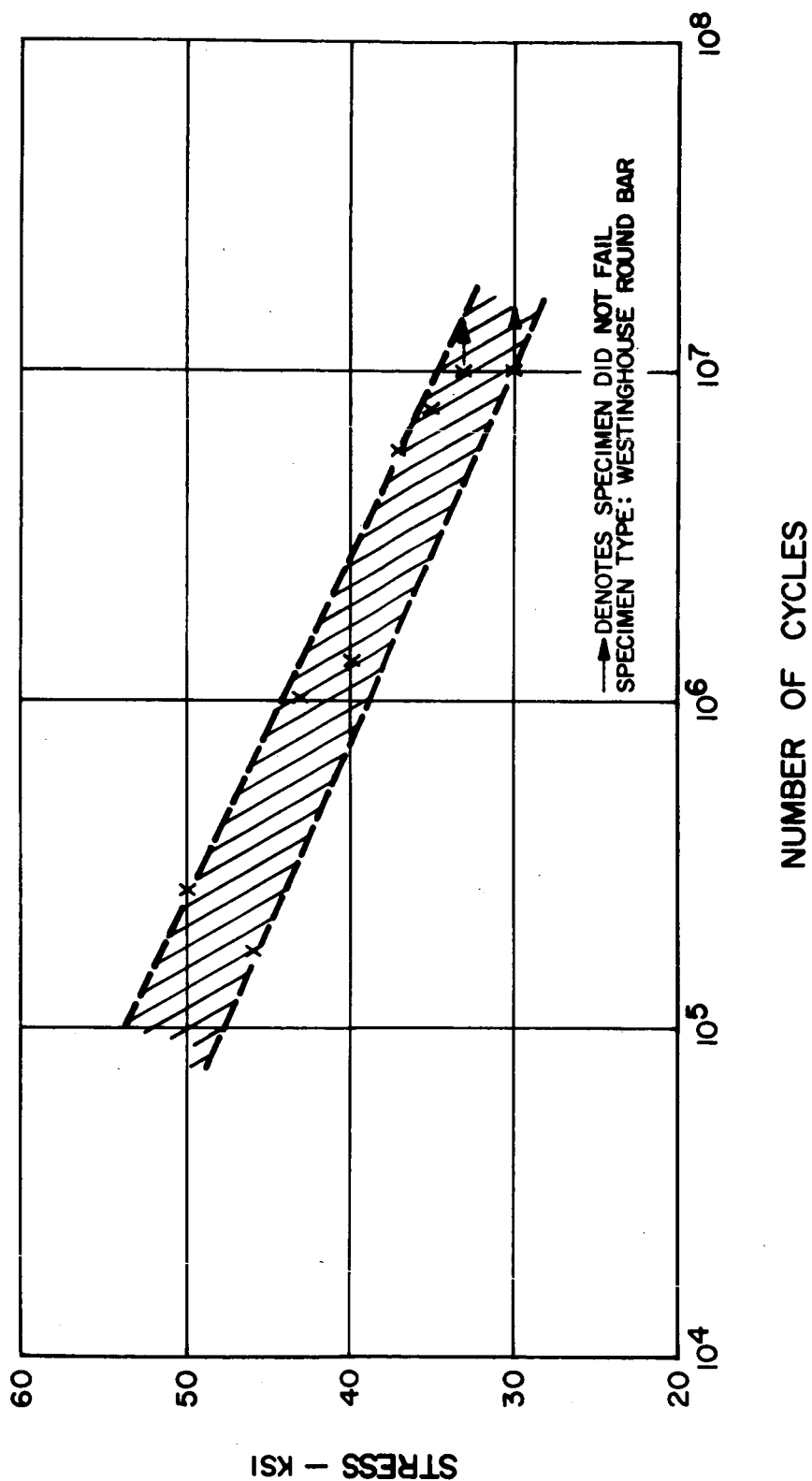


Figure 18 - Fatigue Test Results Obtained at Room Temperature for Columbium-1 Percent Zirconium

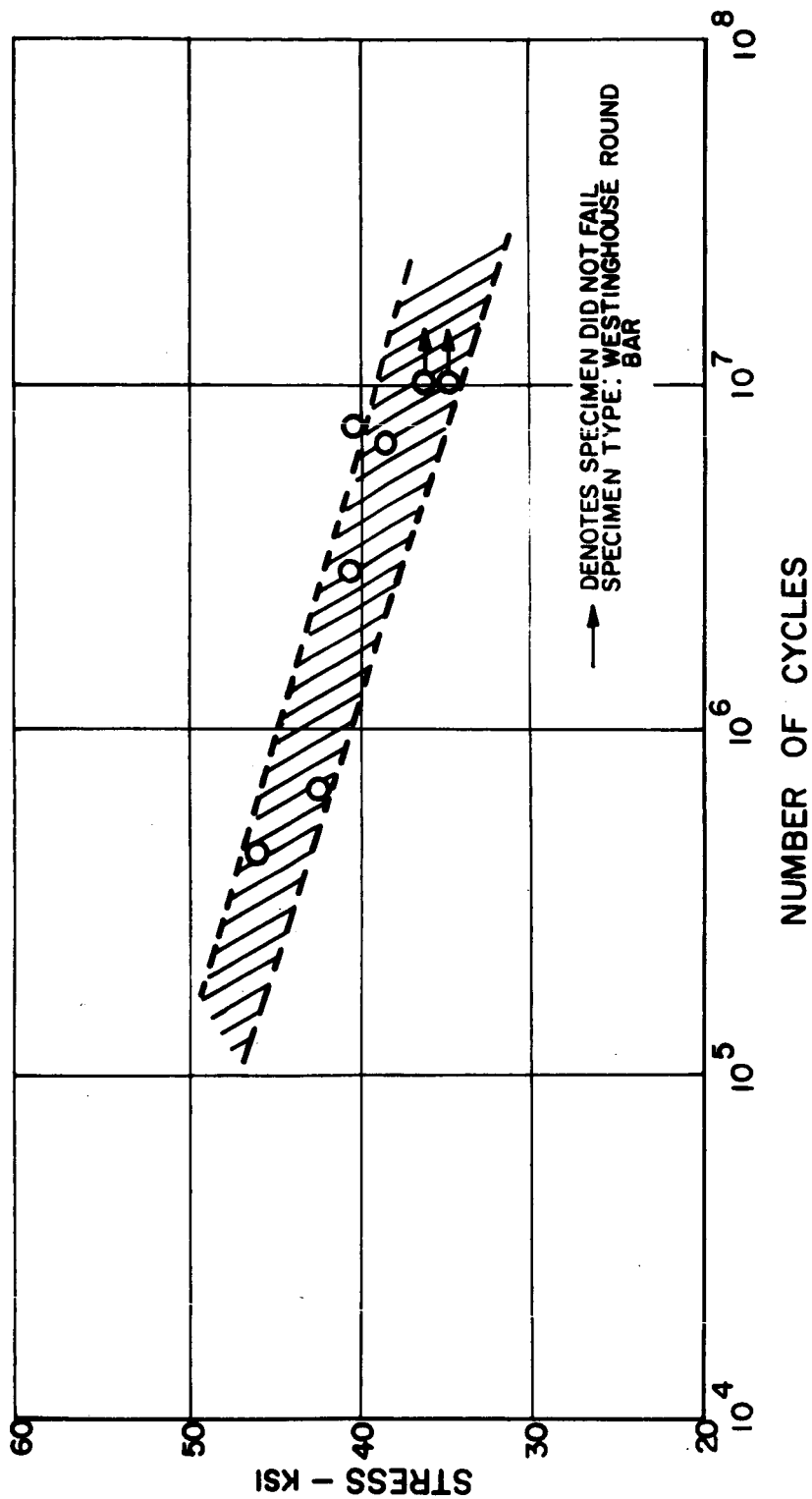


Figure 19 - Fatigue Test Results Obtained at Room Temperature for Columbium-1 Percent Zirconium Coated with Iron Titanate

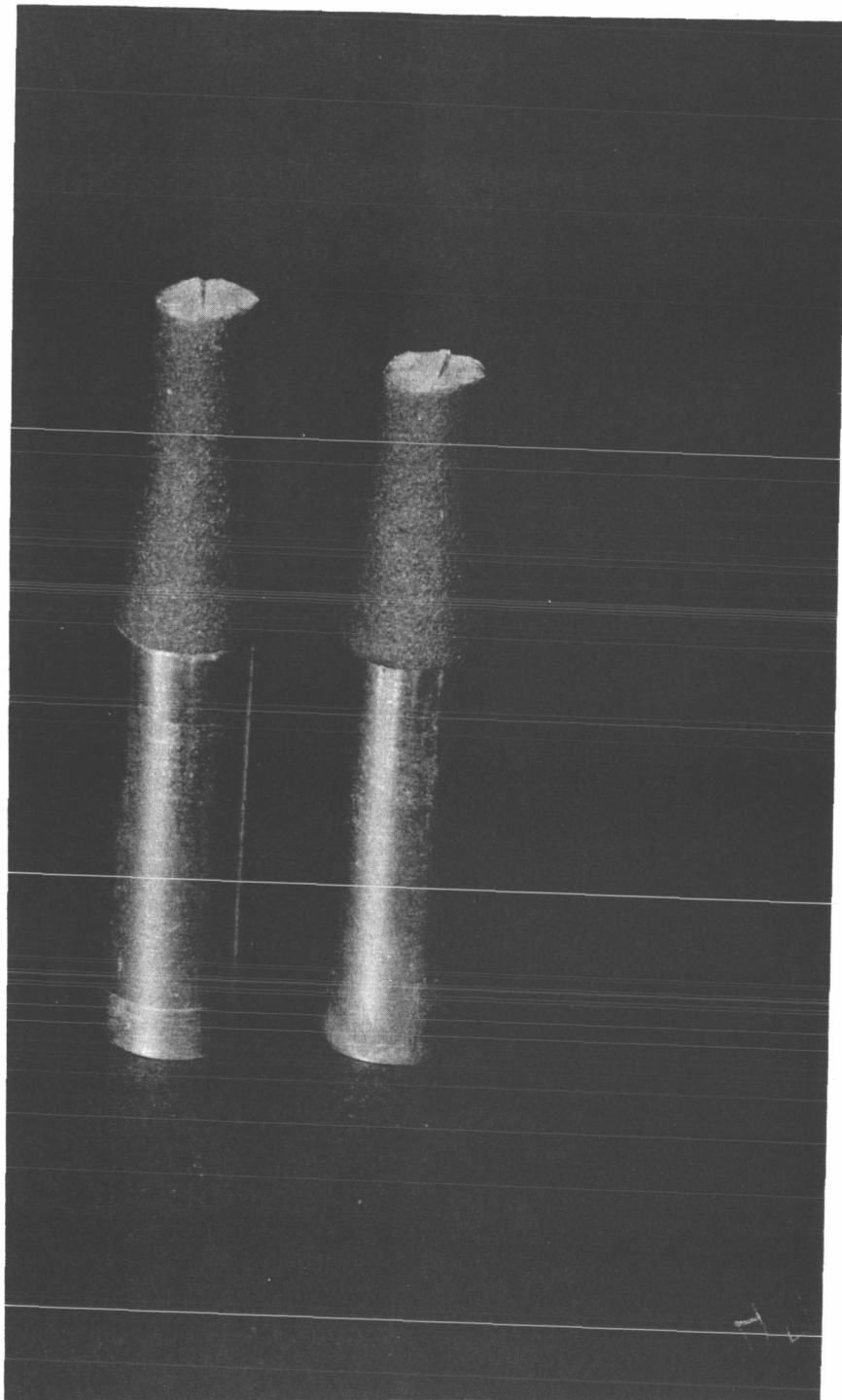


Figure 20 - Fractured Columbium-1 Percent Zirconium Fatigue Specimen Coated With Iron Titanate

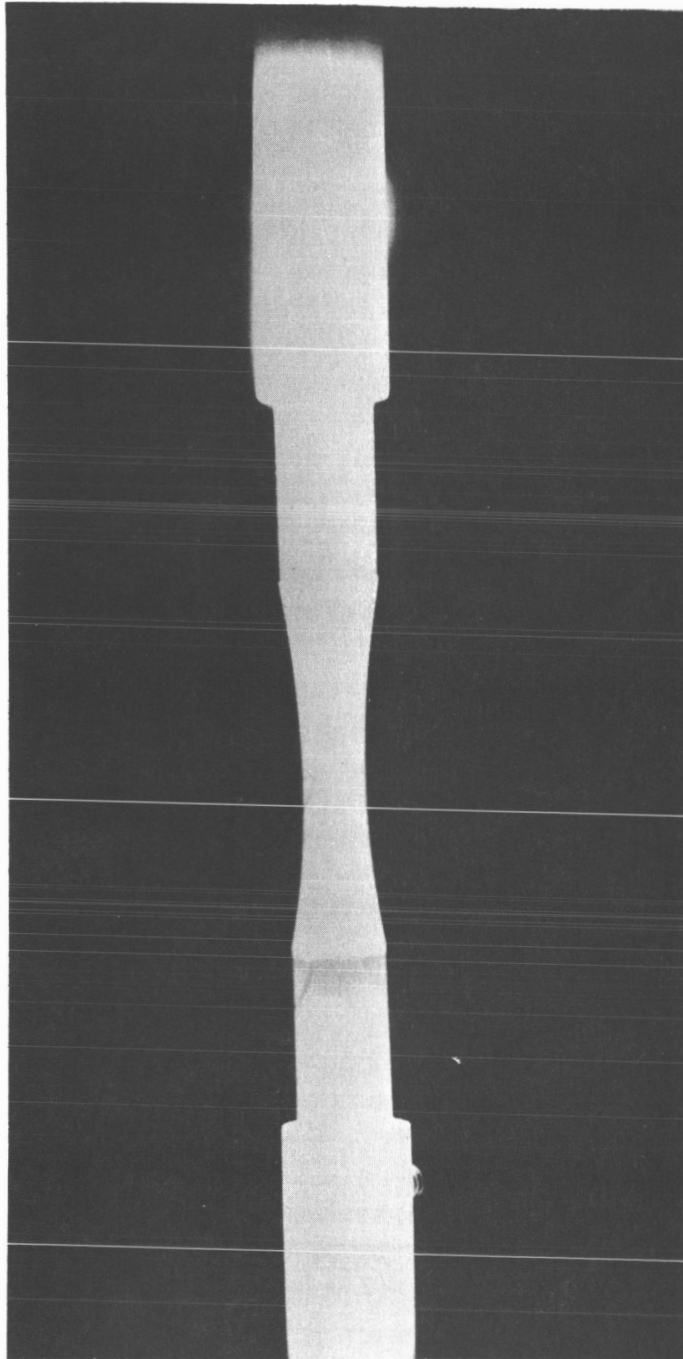


Figure 21 - Columbium - 1 Percent Zirconium Fatigue Specimen
Coated With Iron Titanate and Heated to 1500°F
for Coating Separation Inspection

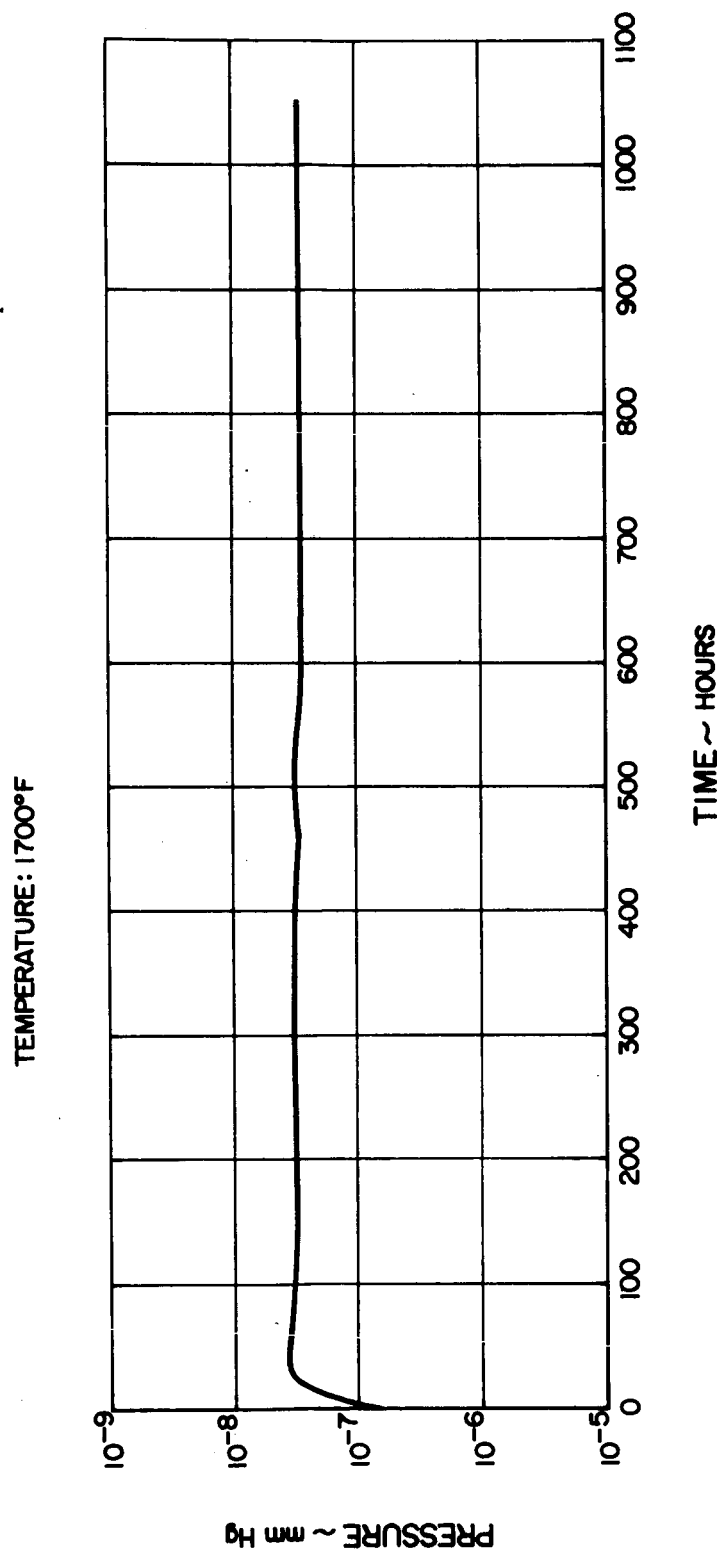


Figure 22 - Chamber Pressure During Testing of Columbium-1 Percent Zirconium
Tube Coated With Aluminum Oxide-Aluminum Titanate

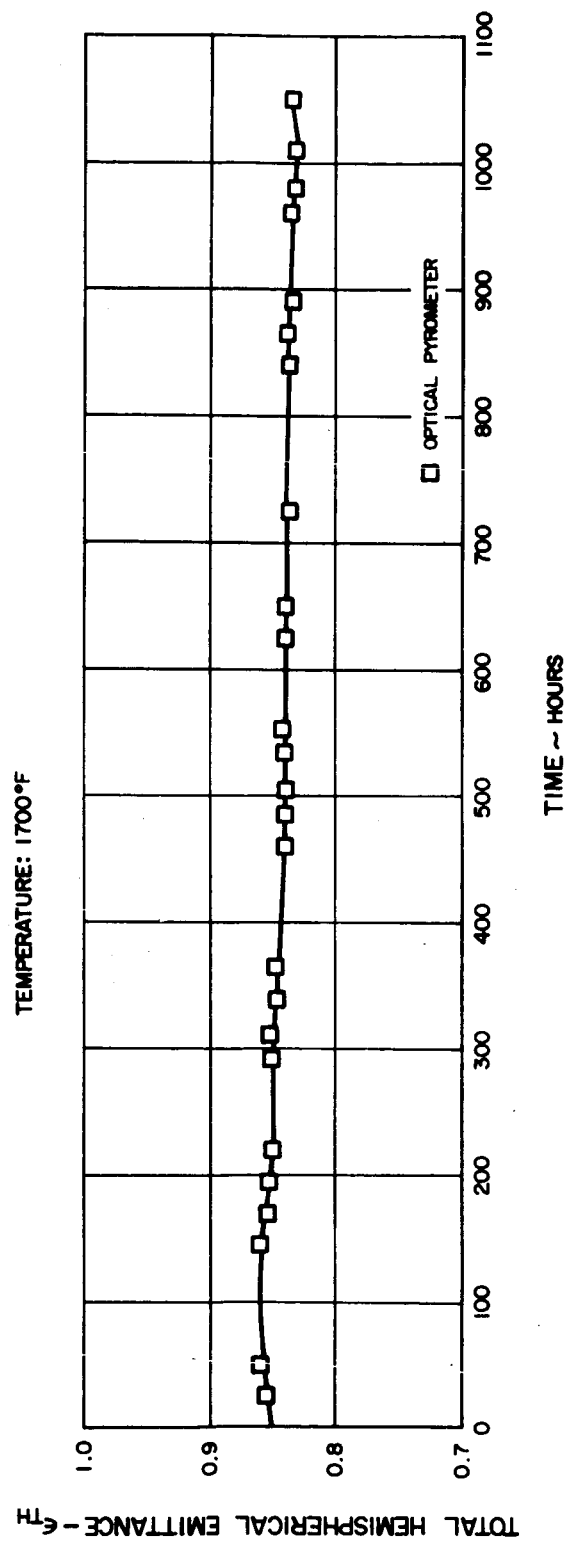


Figure 23 - Total Hemispherical Emittance of Columbium-1 Percent Zirconium
Tube Coated With Aluminum Oxide-Aluminum Titanate

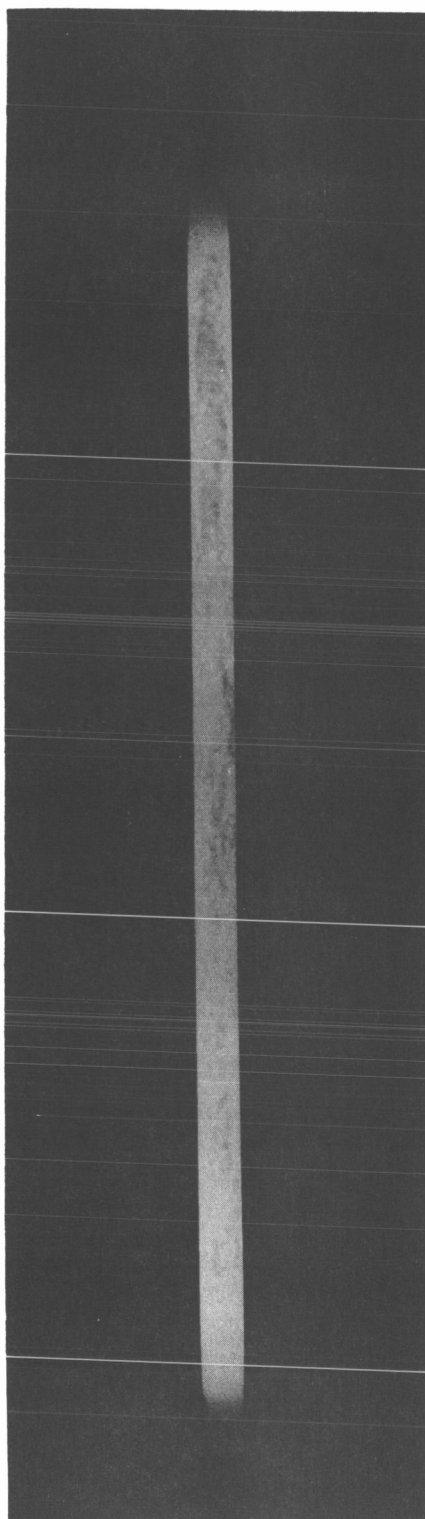


Figure 24 - Appearance of Columbium - 1 Percent Zirconium
Tube Coated With Stabilized Titanium Oxide Composition
After 50 Hours of Long-Term Testing

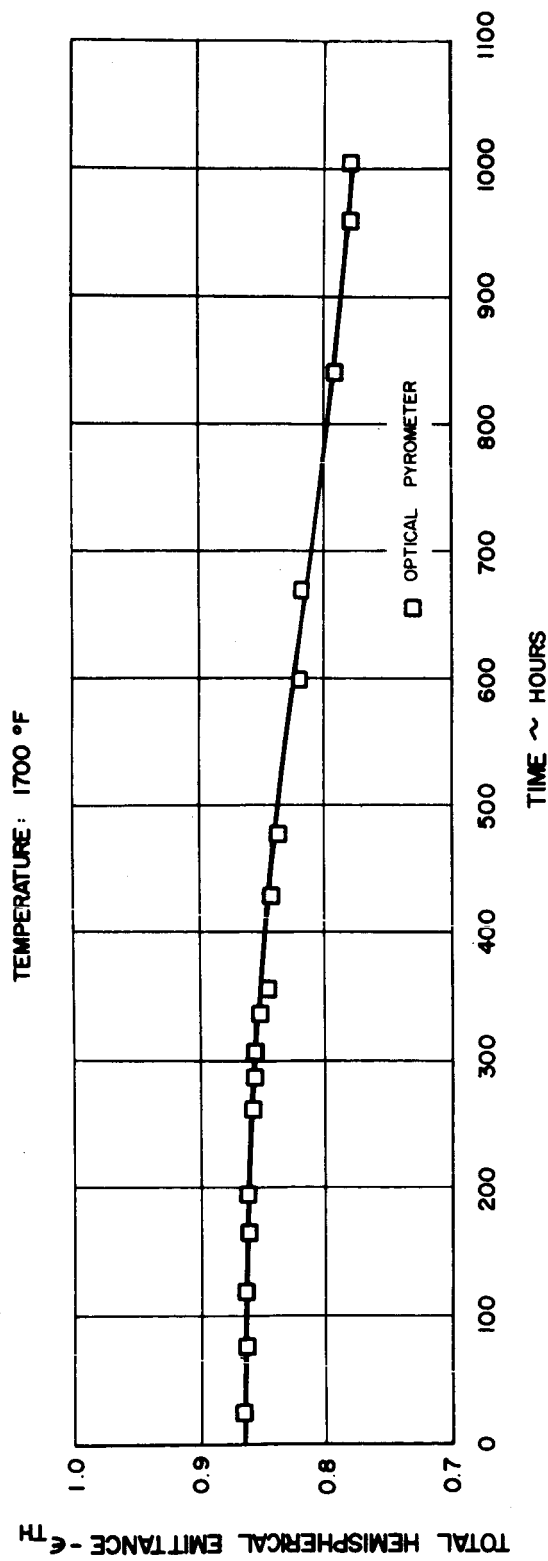


Figure 25 - Total Hemispherical Emittance of Columium - 1
Percent Zircalium Tube Coated With Stabilized
Titanium Oxide Composition

O.D. - .250"
I.D. - .230"

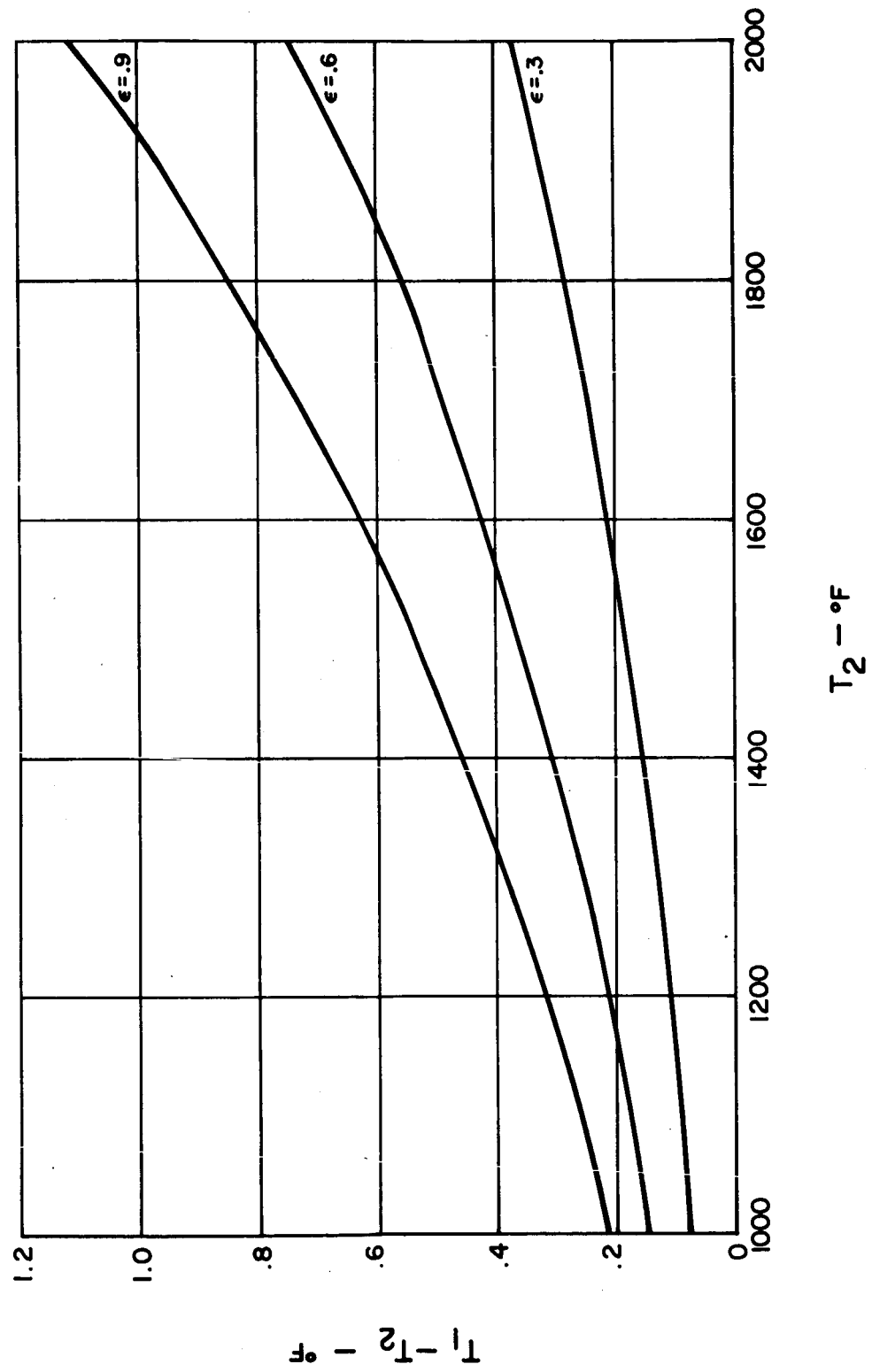


Figure 26 - Temperature Drop Across 10-Mil Wall of AISI-310 Stainless Steel Tube

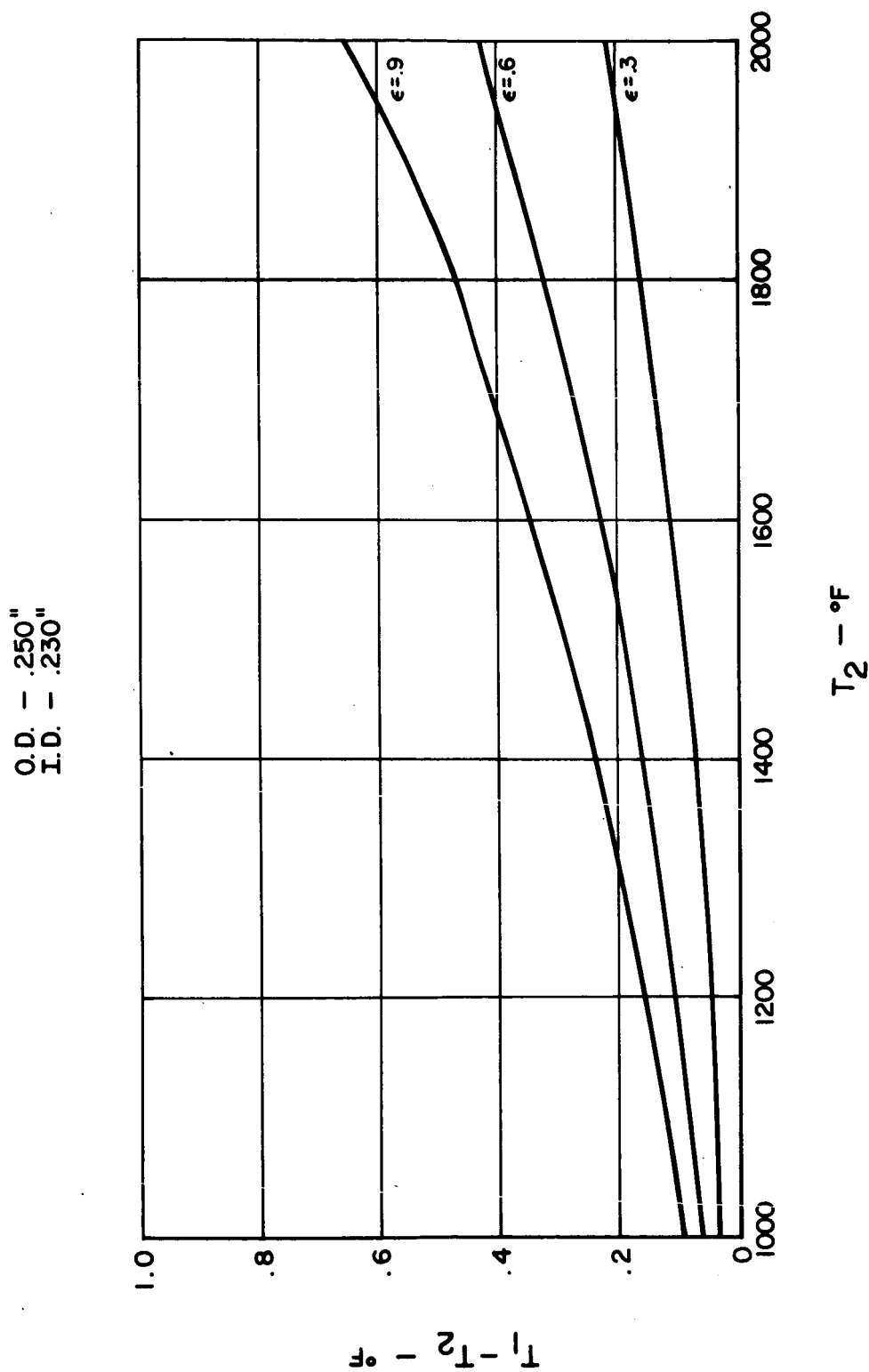


Figure 27 - Temperature Drop Across 10-Mil Wall of Columbium-1 Percent Zirconium Tube

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